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Limited Evaluation of Handling Qualities for a Supersonic Tailless Air Vehicle (Project "HAVE STAV")

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FINAL TECHNICAL INFORMATION MEMORANDUM

Approved for public release; distribution is unlimited.

AIR FORCE FLIGHT TEST CENTER
EDWARDS AIR FORCE BASE, CALIFORNIA
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14. ABSTRACT

This report presents the results of Project HAVE STAV, a limited evaluation of the handling qualities for a Supersonic Tailless Air Vehicle (STAV). This test program used the Calspan-operated Total In-Flight Simulator to test the powered approach handling qualities of a Northrop Grumman STAV model. The test team developed an optimized control system prior to flight testing. The handling qualities were determined using the STAV model coupled with either the baseline or optimized control system. The USAF Test Pilot School, Class 07A, conducted six flight test sorties totaling ten hours at Niagara Falls International Airport, New York, from 10 to 13 Sep 2007. Flight testing included a series of precision and lateral offset landing tasks, which were accomplished at different crosswind conditions. All test objectives were met.

15. SUBJECT TERMS
Instantaneous Center of Rotation, LAMARS (Large Amplitude Multimode Aerospace Simulator), Long-Range Strike Aircraft, STAV (Supersonic Tailless Air Vehicle), TIFS (Total In-Flight Simulator), Approach, Landing, VSS (Variable Stability System), Handling Qualities, Flight Testing

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PREFACE

The HAVE STAV test team would like to thank the Air Force Research Laboratory (AFRL) for their generous support, from both a financial and technical standpoint. This project would not have been possible without either their funding or their Large Amplitude Multimode Aerospace Simulator (LAMARS) facilities and personnel. We would also like to thank Calspan for their reconstitution of the Total In-Flight Simulator (TIFS) aircraft, and their engineering support during flight testing at Niagara Falls.

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EXECUTIVE SUMMARY

This final technical information memorandum presents the test procedures and results for the HAVE STAV (Supersonic Tailless Air Vehicle) Test Management Project (TMP). The HAVE STAV test team performed flight tests in the Calspan Total In-Flight Simulator (TIFS) aircraft to determine the handling qualities of the STAV model and associated control systems. The STAV model was a conceptual flight control suite developed by the Northrop Grumman Corporation (NGC). The Commandant of USAF Test Pilot School (TPS) directed this program at the request of the Air Force Institute of Technology. All testing was accomplished under TPS Job Order Number M07C0600. In order to accomplish the test objectives, a total of ten hours on six flight test sorties were flown on the Calspan-operated TIFS. All flight testing was conducted at Niagara Falls International Airport, NY, during 10-13 September 2007.

The HAVE STAV test aircraft was the TIFS, an NC-131H (commercial Convair 580) twin-turboprop transport aircraft modified as a six degree-of-freedom in-flight simulator. The system under test was the NGC STAV model. Prior to flight testing the STAV model, the test team used the Air Force Research Laboratory's Large Amplitude Multimode Aerospace Simulator (LAMARS) to: familiarize the test team with the flying qualities of the model, explore the effectiveness of various feel system and configuration changes, design an alternate control system, assist with developing analysis techniques, and refine the test methodology.

The test team successfully completed a limited evaluation of the handling qualities for the STAV model, meeting all three objectives set forth in the test plan. First, the test team determined that the handling qualities of the baseline STAV model varied according to the phase of flight. Although not formally evaluated by the pilots, the handling qualities during the approach tasks at altitudes greater than 100 ft AGL were noted by the evaluator pilots as good, with no objectionable tendencies in aircraft response or motion. However, during the flare and landing, the handling qualities of the aircraft were objectionable to the pilots, who commented on the high pitch sensitivity and lack of predictability when attempting to land. The pilots had the most difficulty in simultaneously meeting both the vertical velocity and the longitudinal landing distance criteria at touchdown.

The test team then compared the control system optimized in LAMARS to the baseline STAV control system. The performance and predictability differences observed in LAMARS were portrayed in Cooper-Harper ratings, PIO ratings, and in a measure of pilot aggressiveness and duty factor (the speed and percentage of time that the pilot moved the inceptor). Finally, the test team determined the flying qualities for the TIFS simulation of the STAV flight control system using a series of programmed test inputs and semi-open-loop capture tasks. The results show that the STAV model as implemented on TIFS had the same flying qualities as the model simulated both at NGC and in LAMARS. The test team demonstrated that the handling qualities of a notional aircraft could be determined using an aircraft with a variable stability system.

Overall, several recommendations for more testing were made to investigate the effects of different influences on the handling qualities of the STAV model. These influences could include the use of a heads-up display with predictive symbology (such as a steady-state flight path predictor), different control systems (such as a flight path angle or pitch rate controller), or configuration changes (such as an automatic spoiler retraction). Further testing should focus on the flare and landing phase of flight, which proved to be the most difficult during STAV flight testing.

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INTRODUCTION

Background

In response to Department of Defense plans to develop a new land-based, long-range strike capability, the Northrop Grumman Corporation (NGC) began a design program. This program included several different concepts, including a long-range strike aircraft and two regional bombers. These aircraft were designed to meet all Air Force mission threshold range and speed goals, resulting in design concepts that differed from conventional strike aircraft in several ways. First, for stealth and speed reasons, these supersonic aircraft had no tails. Second, the cockpit location was well aft of a standard cockpit location to reduce drag and aid in stability. Third, driven by the stealth requirement, crew visibility out of the cockpit was extremely limited, meaning that most, if not all, of the pilot visibility outside the cockpit would have to be synthetic. Finally, the instantaneous center of rotation of the aircraft was located far forward of a conventional aircraft's center of rotation. Rather than being located near the center of gravity (CG), the instantaneous center of rotation was thirty feet in front of the CG, almost collocated with the cockpit. This meant that the initial flight path response to a given pitch input would be opposite the direction of the input. This response would be most pronounced to the pilot during approach and landing, where an input to climb would initially result in motion towards the ground. The sink rate perceived by the pilot in the cockpit would be much less than the actual sink rate of the landing gear, resulting in a potentially dangerous rate of descent.

All of these non-conventional design aspects combined to form an aircraft with a supersonic tailless delta configuration. Figure 1 shows an artist's rendering of a potential Supersonic Tailless Air Vehicle (STAV). Such vehicles are known to be aerodynamically complex aircraft with distinctive flight dynamic characteristics and intricate flight control laws. The pilot's opinion of the aircraft was based on, but not limited to: the pilot-vehicle interface, closed loop handling qualities, and physical motion cues. A handling qualities evaluation of this aircraft was therefore important to ensure that the aircraft control laws and flight control system had been properly designed and modeled.

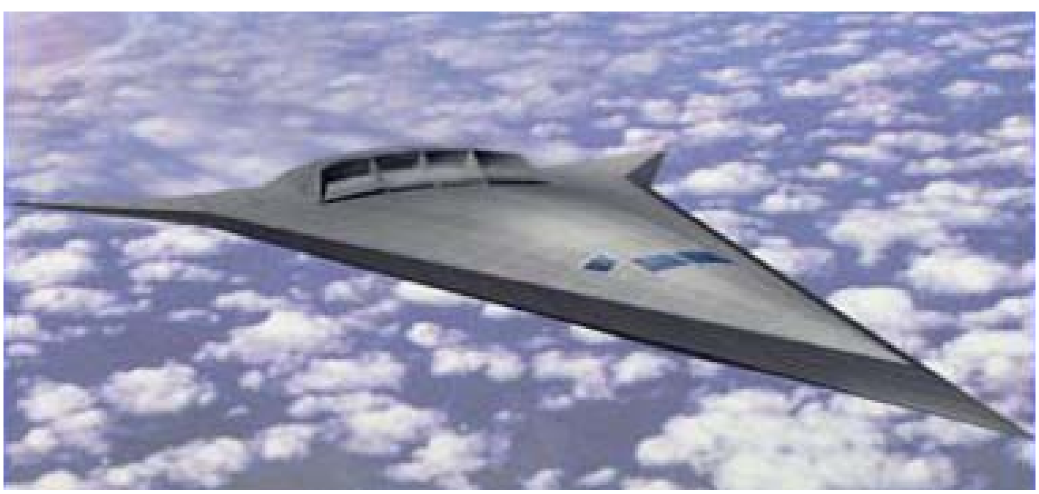

Figure 1. Supersonic Tailless Air Vehicle

Test Objectives

The overall test objective was to conduct a limited evaluation of the handling qualities of the STAV flight control system model during the powered approach phase of flight. The specific test objectives were:

- Determine the powered approach handling qualities of the baseline STAV model.
- Compare the Large Amplitude Multimode Aerospace Simulator (LAMARS) optimized control system to the baseline STAV control system.
- Determine the flying qualities for the Total In-Flight Simulator (TIFS) simulation of the STAV flight control system.

All three test objectives were met.

Test Item Description

Since the STAV was still in the proof-of-concept phase, the handling qualities had to be evaluated via simulation. NGC developed a flight control suite that could be evaluated for handling qualities prior to implementation on an actual STAV. For the purposes of this test, the system under test was version two of the STAV flight control suite, which was implemented on the TIFS. This suite was the basis for both the baseline and LAMARS optimized testing. Test item details were proprietary NGC information and could only be distributed in accordance with NGC requirements regarding proprietary information.

The test team conducted simulator testing of the STAV model on LAMARS at Wright-Patterson AFB, OH. The simulator testing allowed the team to develop an optimized control system to be compared to the baseline STAV control system. The properties for the systems evaluated during this flight test are listed in table 1.

Table 1. STAV Control Systems

Control System	Breakout Forces (Pounds)	Friction Forces (Pounds)	Force Gradient (Pounds/Inch)	Longitudinal Travel (Inches)	Alternate Control Technique
Baseline	1	1	2.6	3.2 forward / 4.2 aft	N/A
LAMARS Optimized	1	1	13.5	3.2 forward / 4.2 aft	Spoilers retracted at 30 ft AGL

The test aircraft was the USAF Air Vehicles Directorate TIFS NC-131H, a commercial Convair 580 twin-turboprop transport modified as a six degree-of-freedom in-flight simulator, shown in figure 2. The TIFS aircraft was operated under a cooperative research and development agreement for the USAF by the Calspan Corporation and was maintained and operated by Calspan's Flight Research Group in Niagara Falls, NY. The TIFS aircraft provided

in-flight simulation capabilities for advanced flying qualities and display research. TIFS was also used to demonstrate advanced flight control concepts and avionics systems to test pilots and engineers (reference 1). At nominal NC-131H approach speeds, the TIFS aircraft had the capability to generate the effects of up to a 15 knot crosswind or negate an actual 15 knot steady state crosswind using side force generators on the wings. Due to the high hinge forces present at the HAVE STAV approach speeds, the actual crosswind capability was limited to only a 7-knot generation or reduction of crosswind.

Figure 2. Total In-Flight Simulator (TIFS)

Test Program Chronology

The test team received the program information document on 17 April 2007. The test concept letter was completed on 21 May 2007 and provided the focus for the test concept meeting conducted on 4 June 2007. A test plan working group with Calspan, Northrop Grumman, Air Force Research Laboratories, and the Air Force Institute of Technology was conducted on 13 July 2007. It included discussion of the test team objectives and plans for buildup training in the T-38 and LAMARS. This meeting was followed by several other teleconferences conducted to discuss the details of the test plan and execution. The T-38 training was conducted the week of 3 August 2007, and consisted of a dedicated sortie for each pilot to define and practice the approach and landing tasks that were planned for the LAMARS and TIFS testing. LAMARS testing was conducted on 6-7 August 2007, and included both the baseline STAV control system and an alternate system which the test team optimized on site (reference appendix B). Both the baseline and optimized control systems were then provided to Calspan for implementation onto TIFS. A combined technical and safety review board was conducted on 16 Aug 2007 to review and approve the HAVE STAV test and safety plan.

The TIFS flew a functional check flight on 23 August 2007 in order to ensure that all normal aircraft and variable stability systems could be safely operated. The STAV model was integrated

onto a “hotbench” setup at Calspan in an effort to minimize the time delay encountered when running the STAV model in combination with the TIFS variable stability system. This effort helped to minimize the time required to integrate the STAV model onto the aircraft, which began on 27 August 2007 and was completed on 31 August 2007. Calspan flew TIFS calibration sorties on 5-6 September 2007. These flights were used to ensure that the TIFS simulated STAV response would match the baseline STAV model response, that the resultant time delay of the STAV-TIFS interaction was minimized, and that the approaches to simulated touchdown could be conducted safely. The lessons learned from these flights were integrated into the planned test procedures prior to the test team arriving on 10 September 2007. The test team conducted ground training on TIFS to familiarize the pilots with the displays, variable stability system, and egress procedures of the aircraft. The test team conducted ten hours of flight testing from 10-13 September 2007. A total of six test flights were flown, as shown below in table 1. A detailed summary of the test points flown is presented in appendix D.

Table 2. Summary of Test Flights

Flight	Duration	Description	Test Crew
1	2.0	10 Sep 07 1410L / TIFS flight 2498	Speares, Neff, Porter
2	1.0	11 Sep 07 0940L / TIFS flight 2499	Domsalla, Cook, Gray
3	2.0	12 Sep 07 1010L / TIFS flight 2500	Quashnock, Porter, Domsalla
4	2.0	13 Sep 07 0740L / TIFS flight 2501	Quashnock, Neff, Speares
5	2.0	13 Sep 07 1030L / TIFS flight 2502	Domsalla, Cook, Quashnock
6	1.0	13 Sep 07 1510L / TIFS flight 2503	Speares, Cook, Gray

A preliminary review of the flight testing was conducted at Calspan on 14 September 2007, in order to garner immediate lessons learned and to discuss the data reduction and analysis. All data not provided to the test team while on site at Calspan were delivered the week of 17 September 2007.

TEST AND EVALUATION

The overall test objective was to determine the handling qualities of the Supersonic Tailless Air Vehicle (STAV) flight control system model during the powered approach phase of flight. Cooper-Harper ratings (CHR) were the primary evaluation metric. This rating scale is described in more detail in reference 12, “The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities.” Pilot workload and task performance were used to assign a CHR. The desired and adequate performance criteria were developed by the test team in conjunction with the model developer based on previous experience and expected design limitations. Table 3 lists the desired and adequate performance criteria used in testing. In addition, touchdown airspeed had to be greater than 165 knots, and touchdown pitch attitude had to be less than fifteen degrees. Detailed descriptions of the test maneuvers, as well as visual representations of the offset and touchdown point, are presented in appendix C.

Table 3. Performance Criteria

Precision Landing and Lateral Offset Landing	Desired	Adequate
Landing zone	±25 ft laterally +1000 / -500 ft longitudinally	±50 ft laterally +1500 / -750 ft longitudinally
Maximum bank angle at touchdown	± 5 degrees	± 7 degrees
Maximum touchdown sink rate	4 ft/sec	6 ft/sec
Deviation from runway heading at touchdown	± 2 degrees	± 4 degrees

In addition to a Cooper-Harper rating, a Pilot In-the-loop Oscillation rating (PIOR) was given by the pilot if a PIO was encountered during the approach and landing task. If a PIO was encountered, the pilot rated it according to the scale and provided comments on how objectionable the motion was and what effect it had on pilot opinion. The PIOR was used as another measure of performance in determining the handling qualities of the STAV model. The CHR and PIOR scales are presented in appendix E.

An additional method used to investigate the STAV handling qualities was measuring pilot aggressiveness and duty factor when conducting the different approach and landing tasks. Pilot aggressiveness was determined by measuring the speed of the inceptor movements, while duty factor was a measure of the percentage of time the pilot was “in-the-loop”, moving the inceptor. This method was used post-flight to compare the pilot’s perception of workload and predictability during the tasks with the actual inceptor movements.

Flight testing consisted of multiple runs with three variables (pilot, offset, and crosswind). A factorial design method was initially used with four variables (pilot, offset, crosswind, and approach airspeed) to find the optimal test matrix where the most significant variable interactions would be identified. This matrix was executed in the Large Amplitude Multimode Aerospace Simulator (LAMARS) evaluation to verify predictions and to narrow down the actual test matrix for flight testing. The matrix used in LAMARS testing, including a detailed description of the LAMARS testing and results, is included in appendix B. The flight test matrix is included in appendix D.

LAMARS Testing

Modeling and simulation of the STAV was conducted in the LAMARS full motion simulator on 6-7 August 2007. The main objective was to identify an optimized flight control system, feel system, or technique to flight test in the TIFS. Additionally, the simulator was used to familiarize the test team with the flying qualities of the STAV.

Previous simulator testing conducted by NGC indicated that the optimal flying qualities during powered approach and landing tasks were obtained using an angle of attack (alpha–command) control system. Additional systems tested were a flight-path angle (gamma-command) control system and a pitch-rate (q-command) control system. The HAVE STAV test team conducted a limited evaluation of each of these control systems to determine if they warranted an investigation in the TIFS. These simulations were accomplished using only a heads-down display, because TIFS did not have a heads-up display (HUD) capability.

During previous simulator evaluations of the STAV model conducted by Northrop Grumman, the powered approach and landing tasks that included lateral offset or high crosswinds demonstrated a high pilot workload and potential for PIO. The forward location of the instantaneous center of rotation and the associated flight path response was a likely contributor to this susceptibility. As the pilot tried to make aggressive corrections back to the runway, the initial motion was in the opposite direction of the commanded motion in both pitch and yaw. In an effort to improve handling qualities, the HAVE STAV test team studied the effects of increasing longitudinal inceptor force gradients and the effects of spoiler retraction on flare characteristics.

LAMARS Testing Procedures

Simulator testing was conducted in three phases. The first phase of testing focused on a familiarization with the flying qualities and a comparison of the alpha, gamma, and q-command control systems. Each pilot flew the baseline STAV model with each of these control systems. While flying each controller at altitude, the pilot accomplished a handling qualities evaluation, which consisted of a series of impulses, steps, and semi-closed loop capture tasks in each axis. The pilot then flew two or three practice approaches before flying the tasks for data. This procedure was done to familiarize the pilot with the flare sight-picture and pacing. Each pilot developed a technique for accomplishing the flare during this initial phase, after which the pilots decided on a standardized flare technique that involved altitude calls above ground and a timed power reduction. Each pilot accomplished the precision approach and lateral offset tasks with and without crosswind, as well as a vertical offset landing task. These maneuvers were accomplished to see if offsets in different axes produced different workloads for the pilots.

The second phase focused on modifying the feedback command control system judged best during phase one of the testing. This modification involved automatically increasing the force gradient in the longitudinal axis when passing through a set altitude above ground. Both the value of the force gradient and the altitude of the change were varied in order to yield a more

repeatable and predictable flare. The first pilot to test the system conducted the test tasks while varying both the altitude and value of the force gradient change. The values judged best by the first pilot were passed on to the next pilot, who began with these values and altered them until the values were set to an optimized level. To determine the effects of spoiler retraction, the force gradient was reset to the baseline and the spoilers were automatically retracted when passing through a certain altitude. The altitude of this retraction was optimized in the same manner as the force gradient changes. The effect of both of these modifications on pilot opinion and performance was compared to the baseline system. The two modifications were then made simultaneously, optimized for pilot opinion and performance.

The third and final phase focused on a comparison between the optimized and baseline control systems and test preparation using the optimized system developed in phase two. The optimized system was tested by all three pilots to ensure that they agreed on the chosen values. All the pilots then tested the baseline system and compared their results to the previous baseline testing to ensure that learning was not the sole source of the improvement in pilot opinion and performance. The test team staff pilot then flew both the baseline and optimized system in order to evaluate the difference between the two systems. The flight test engineers and flight test weapon systems officer then flew to familiarize themselves with what the pilots were feeling and to practice the test procedures to be used in flight testing.

LAMARS Testing Results

Results from the first phase of testing closely matched the results obtained from NGC during previous simulator testing. All three test team pilots agreed that the alpha command system should be tested further in TIFS, even though it required some improvement. The gamma controller was slightly less intuitive to the pilot, but obtained comparable results to the alpha controller during low workload tasks. If corrections were not required due to high crosswinds or lateral offset landings, and workload remained low, the gamma controller provided performance results comparable to or slightly better than the alpha controller. However, in cases where lateral corrections were required, the aircraft motions and control inputs were unnatural, and if actual instrument conditions were present, the pilots could easily become spatially disoriented. The pitch rate controller provided the biggest challenge for all of the pilots and was the most disorienting to use. It was difficult to predict the response of the aircraft to a longitudinal input, making it hard to maintain the glide slope and flare the aircraft.

Following this first phase of testing, the team collectively decided to conduct all further testing and control system modifications with the alpha command system.

During the first phase of testing, pilots noted that the flare was the most difficult part of the approach tasks. Handling qualities up and away were not problematic. Pilots commented that maintaining the appropriate glide slope and alignment with the runway were not challenging, and could be considered satisfactory. However, once close to the ground (below 100 feet AGL), the longitudinal inputs required to flare the aircraft were difficult to control. The flare typically required a tradeoff between satisfying either the landing distance or the vertical velocity evaluation criteria. When the pilot focused on the desired vertical velocity criterion, the typical result was a landing distance of 1500 to 2000 feet from the desired touchdown point. When the

pilot focused on the desired landing distance criterion, the typical result was a hard touchdown between six and ten feet per second.

In order to limit the undesired pitching motions and pilot tendency to over control during the flare, the longitudinal inceptor force gradient was increased just prior to entering the flare. Using the procedures outlined previously, and the pilots came up with optimized values for the force gradient and the altitude of the change. The optimal gradient was found to be five times the baseline gradient, or approximately 13.5 pounds of force per inch of inceptor deflection. The optimal height above ground for the gradient change was 100 feet AGL. These optimal values were based on both Cooper-Harper and PIO handling qualities ratings.

In addition to the increased longitudinal inceptor gradient, the effects of retracting the spoilers during the flare were also observed. Retracting the spoilers minimized the required throttle change to maintain airspeed. Maintaining the appropriate airspeed provided a more natural pitching moment during the flare, and reduced the landing gear sink rate generated when pulling aft on the inceptor. Automatic spoiler retraction reduced this sinking motion during the flare. An automatic spoiler retraction height of 30 feet AGL was decided upon by the pilots as optimal. This altitude allowed the spoilers to completely retract just as touchdown occurred.

Coupling the spoiler retraction with the increased longitudinal inceptor force gradient improved the flare handling qualities. Using the optimized control system, the handling qualities were regularly acceptable or better during the landing tasks and were only unacceptable during high crosswind or lateral offset landing tasks. These results were an improvement over the baseline where typical handling qualities were unacceptable. Tables 4 and 5 below show the Cooper-Harper ratings for the baseline and optimized systems, as well as the performance achieved for both systems.

Table 4. Baseline and Optimized CHR

CHR	3	4	5	6	7	8
Baseline	0	1	13	1	22	3
Optimized	4	1	6	1	8	0

Table 5. Baseline vs. Optimized Performance Achieved

	Desired (Total %)	Adequate (Total %)	Inadequate (Total %)
Baseline	1 (2.5)	14(35)	25 (62.5)
Optimized	5 (25)	7 (35)	8 (40)

The vertical velocity encountered during the flare for both the baseline and optimized control systems is shown in figure 3. The optimized system showed no tendency to increase in vertical velocity as the inceptor was pulled aft, while the baseline system did.

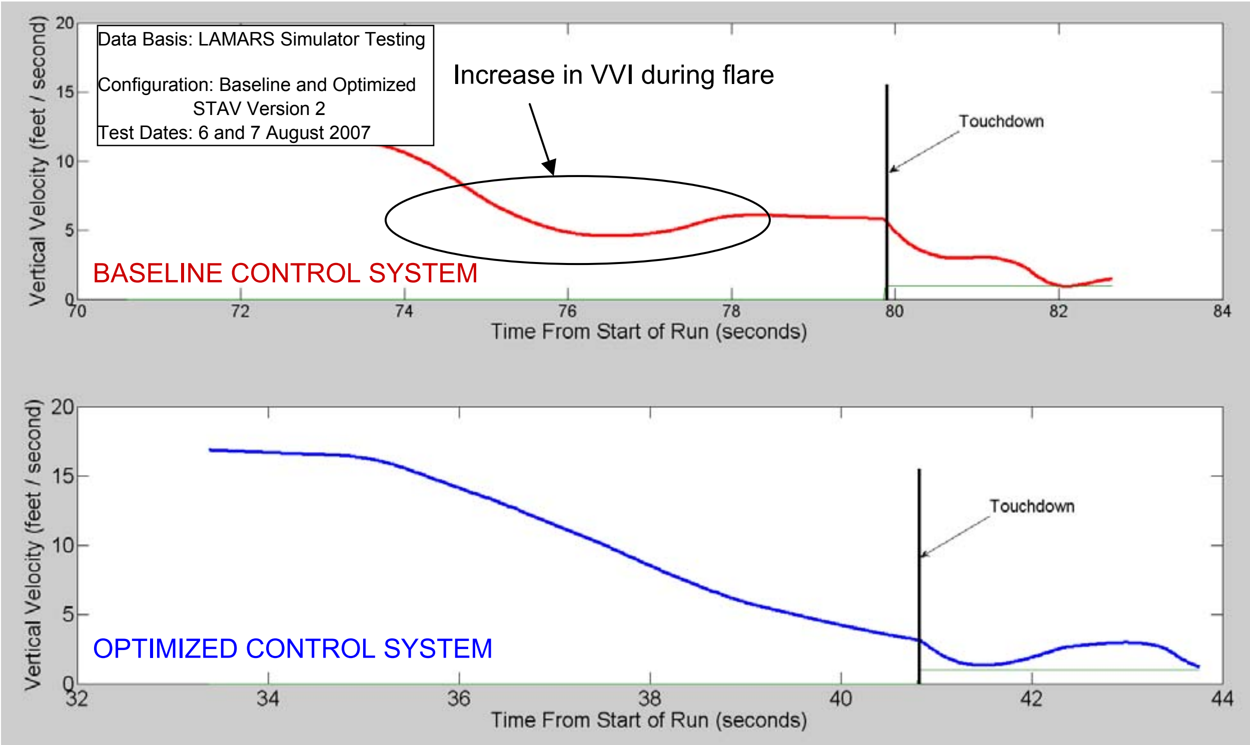

Figure 3. Vertical Velocity of Baseline vs. Optimized Systems

After testing was complete, another method was created to determine differences between the baseline and optimized systems. The inceptor velocity was measured as a function of time, and used as a metric for pilot aggressiveness. The percentage of time that the pilot was moving the inceptor over a given period was also measured, and used as a metric for duty factor. These two metrics were then plotted against one another to determine if aggressiveness and duty factor differed between systems and influenced pilot opinion on performance predictability. Figure 4 depicts pilot aggressiveness and duty factor for both the baseline and optimized systems. It shows no significant differences between the baseline and optimized systems. Both systems varied widely in overall aggressiveness and duty factor, leading to the lack of predictability in performance achieved.

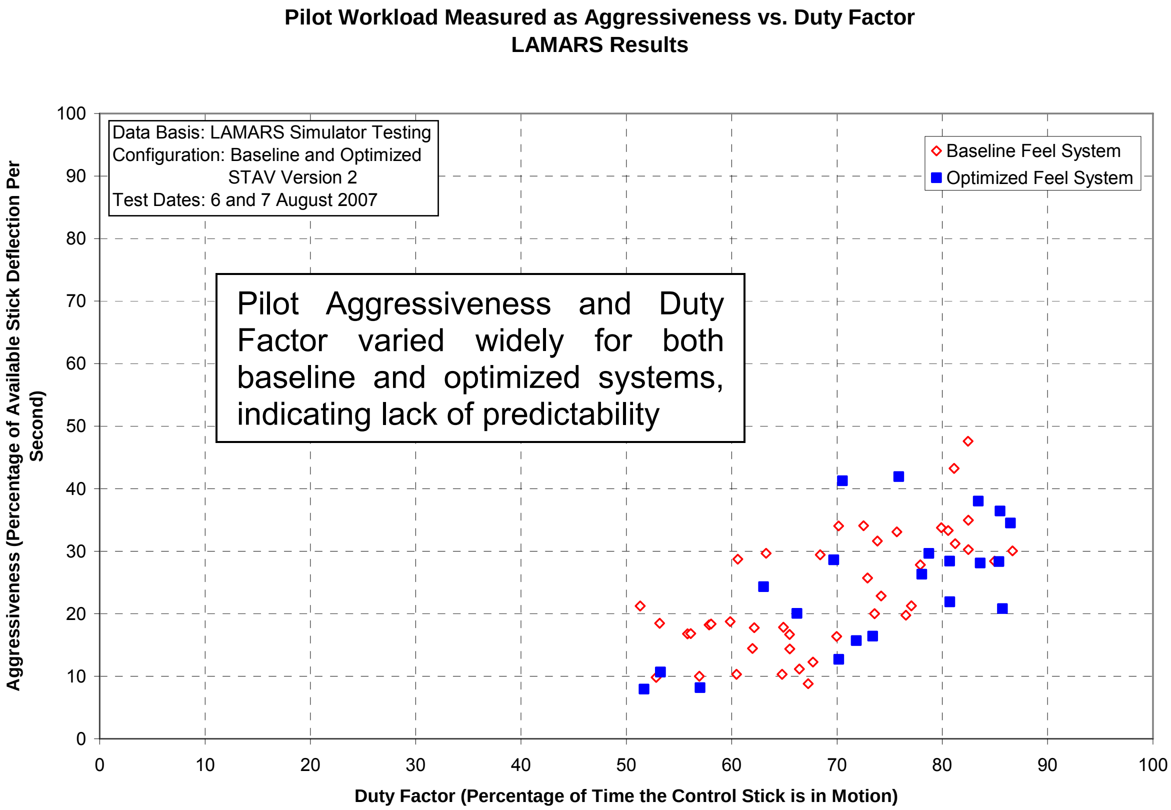

Figure 4. LAMARS Pilot Aggressiveness and Duty Factor

Following the development of the optimized system, the baseline system was retested to ensure that improved handling qualities were not attributed to practice alone. When retesting to the baseline conditions, the same tendencies to over-control during the flare were observed. Task performance in the flare was again unpredictable. Table 6 shows the original baseline performance achieved on the first day of testing compared to the final baseline performance achieved on the second day of testing.

Table 6. Baseline Performance Achieved

	Desired (Total %)	Adequate (Total %)	Inadequate (Total %)
Day 1 Baseline	1 (4.5)	7 (31.8)	14 (63.6)
Day 2 Baseline	0 (0)	7 (38.9)	11 (61.1)

TIFS Testing

Flight testing of the STAV model was conducted on the Total In-Flight Simulator (TIFS), a six degree of freedom NC-131H operated by Calspan. Flight test sorties were accomplished from 10-13 September 2007 in the airborne traffic pattern at Niagara Falls International Airport. The goal of testing was to meet all three of the test team objectives: determine the powered approach handling qualities of the baseline STAV model, compare the LAMARS optimized control system to the baseline STAV control system, and determine the flying qualities for the TIFS simulation of the STAV flight control system.

Previous flight test programs on TIFS indicated that the optimal time to switch to the Variable Stability System (VSS) and transfer control to the evaluation pilot was on downwind. This procedure would allow the pilot to gain an initial feel of the system when turning base and final, prior to conducting the approach and landing task. The HAVE STAV team used the TIFS-generated localizer and glidepath information to ensure repeatability in task performance between the different test pilots. This procedure was essential during the lateral-offset tasks, where a consistent offset point was required. This TIFS capability also allowed the test team to shift the desired touchdown point to a point on the runway with better threshold clearance, enhancing test safety. Finally, the TIFS allowed the team to capture "touchdown" parameters at an actual altitude of 20 feet AGL, since landing gear airspeed restrictions limited testing to low approaches only.

TIFS Testing Procedures

Calspan pilots flew the TIFS in between each run while the evaluation pilot (test team test pilot) was working with the test conductor to assign a Cooper-Harper rating. The test runs commenced once aircraft control had been transferred to the evaluation pilot. The evaluation pilot assumed control and performed the required task. Each evaluation pilot began the sequence of test points with a nominal or baseline precision approach and landing. To increase pilot workload, the crosswinds were increased to seven knots and the approach was repeated. The pilot then flew an offset approach with seven knots of crosswind. Each point was terminated by either a simulated touchdown, a safety pilot termination, or via the safety trips in the variable stability system onboard the TIFS.

In an effort to model the eye height of the STAV, the simulated touchdown plane was set at 20 feet AGL. The planned touchdown point was 1,500 feet down the runway, on centerline, at 20 feet AGL. It was from this point that the landing distance was measured. When passing through the point, the parameters listed in table 3 were recorded and displayed to the test team so that a Cooper-Harper evaluation could be completed. Details of each specific approach task are contained in appendix C.

Baseline STAV Model Results

The handling qualities of the baseline STAV model during powered approach were predominantly unacceptable for the tests completed. A total of 33 approaches were flown with

the baseline feel system, using the order of tasks described above to methodically build up in workload. Cooper-Harper ratings given by all pilots totaled one Level 1 rating, fifteen Level 2 ratings, and seventeen Level 3 ratings. Histograms of the Cooper-Harper ratings are shown in appendix F, figures F-1 through F-7. Pilot In-the-Loop Oscillation ratings were assigned twice, each for non-divergent oscillatory motions. The specific order of test points flown can be found in the test matrix in appendix D.

For all approach types, the driving factor for the unacceptable handling qualities was inadequate task performance. For most baseline feel system approaches, the pilot workload and compensation were both determined to be acceptable.

The purpose of the various approach types was to create tasks that would increase pilot workload (while maintaining the same performance criteria) in order to uncover key handling qualities characteristics. A sequential buildup of workload in the LAMARS was achieved using the task order already described: normal approach, normal approach with crosswind, lateral offset, and lateral offset with crosswind. The escalation in workload with each task was evident in both pilot comments and performance. While this buildup worked in the simulator, the pilots' experience in the TIFS was different.

As expected, the normal precision approach still required the lowest workload. The combined offset and crosswind task remained the highest workload, presumably due to the complex combination of control inputs required. However, correcting for crosswinds was found to require a higher workload than correcting for a lateral offset.

While the lateral offset task required a lower workload than expected, landing performance for these approaches was clearly lower than for the normal approaches. Of nine approaches, seven failed to meet adequate criteria and none achieved desired criteria. However, there was no clear trend in performance inadequacy. Three of the approaches failed to meet adequate criteria for touchdown distance (long), three for sink rate, and four for tail strike pitch attitude. Two of these approaches had multiple inadequacies.

For most of the baseline approaches (19 of 33), conditions included light to moderate turbulence and variable crosswinds both with and without gusts. In these conditions, removing crosswinds was difficult for the TIFS to manage without tripping the VSS by exceeding control surface limits. As a result, many of the "zero-crosswind" approaches were flown without crosswind simulation, which meant flying in actual crosswinds ranging from zero to seven knots. These conditions were perceived by the pilots to have a higher workload than either the lateral offset or steady crosswind tasks themselves. Unscheduled and unpredictable disturbances due to turbulence or gusts required the pilots to continually correct the aircraft's attitude all the way to simulated touchdown. This provided a valuable insight into both pilot aggressiveness and aircraft predictability, as detailed in the next section.

The designed tasks as well as the environmental conditions increased pilot gain to appropriate levels for purposes of these handling qualities tests. Neither the tasks nor the conditions were assessed to be unrealistic for an operational bomber mission. Furthermore, they

revealed the sometimes subtle handling qualities characteristics of the model during approach and landing.

As far as task performance, vertical velocity at touchdown was the critical parameter leading to Level 2 and 3 handling qualities for all approach tasks. Ensuring desired sink rate most often resulted in only an adequate or inadequate longitudinal touchdown point (typically long). The pilots remarked that they lacked sufficient cues to estimate sink rate. Due to the touchdown eye height of the notional STAV (and corresponding simulated touchdown point), peripheral vision did not provide a “ground rush” cue to arrest the sink rate. Without a HUD, all instrumented cues would have required the pilot to be “heads down” during the most critical part of the landing-the flare. The test conductor attempted to provide some sink rate feedback by calling altitude remaining until touchdown at 100 feet, 50 feet, and every 10 feet thereafter. This allowed the pilots’ eyes to remain outside. While these audio cues may have helped, they were not sufficient. Other cues were needed but were not available. Without these cues, the landing became a mechanical exercise where flare height and power reduction were determined strictly by altitude. An appropriate HUD would have improved the flight path and sink rate awareness needed during the visual portion of the landing. In addition, previous simulator testing in LAMARS by NGC indicated that powered approach and landing handling qualities were improved when using a HUD. **Implement a HUD on the STAV. (R1)**[1]

A HUD would present the current aircraft parameters to the pilot. However, due to the aircraft characteristics and overall system time delay, these parameters alone would not be sufficient for the pilot to predictably flare and land the aircraft. Combining the current aircraft parameters with predictive guidance information from a flight director or predictive flight path marker would increase the STAV flight predictability, particularly during flare and landing. Neither a flight director nor predictive flight path marker were used during testing. **Implement predictive guidance on the STAV. (R2)**

The primary flight control characteristic found to be objectionable during the landing phase of the baseline STAV model was pitch sensitivity. The inceptor force gradient was 2.6 pounds per inch. Full aft inceptor deflection was 4.2 inches, requiring a force of only 10.92 pounds. The light control forces required during the flare decreased predictability and increased pilot workload. Baseline inceptor gains were too low during approach and landing, resulting in a loose or light feel, objectionable inceptor sensitivity, and increased duty cycle and aggressiveness. **Increase the inceptor force gradient for approach and landing. (R3)**

An additional factor affecting aircraft predictability in the pitch axis during approach and landing was time delay. Time delay in flight path response, on the order of one second, reduced predictability of pitch inputs, resulting in open-loop, methodical pilot compensation for approach and landing. These techniques included reducing power at specific altitudes, beginning the flare at specific altitudes, and step or impulse inputs followed by a pause to allow the aircraft to respond. This time delay in flight path response was inherent in most delta wing designs. **Reduce the time delay in flight path response. (R4)**

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[1] Numerals preceded by an R within parentheses at the end of a sentence correspond to the recommendation numbers tabulated in the Conclusions and Recommendations section of this report

The focus of the handling qualities discussion to this point has been in the pitch axis, due to its uniqueness in controlling this particular aircraft and due to its criticality in executing an acceptable (safe) landing. However, there were also some interesting discoveries made when making lateral-directional inputs. First, presumably due to the tailless design, lateral accelerations were noted simultaneously with aircraft roll rates. This characteristic was subtle and not objectionable when the pilot commanded roll. When a roll rate was induced by an outside disturbance such as turbulence or gusts, lateral accelerations were more apparent, though still not objectionable. Roll sensitivity during turbulence was also noted.

Another notable characteristic was observed during rolling maneuvers. Due to the design of the alpha-command controller, an upward pitching moment was experienced when rolling into a turn and a downward pitching moment when rolling out of a turn. These moments were due to the flight control system attempting to compensate for the increase in angle of attack it predicted was required for the turn. However, the flight control system overcompensated. This overcompensation required the pilot to impart an unnatural push when rolling into a turn and an unnatural pull when rolling out of a turn. **Reduce the amount of alpha compensation generated during turns. (R5)**

Baseline to Optimized System Comparison

Overall, the comparison of the LAMARS optimized control system (optimized system) with the baseline STAV control system (baseline system) showed that the optimized system had improved handling qualities over the baseline system, as shown in figures F-1 through F-3 and F-5 through F-7 in appendix F. While there was an increase in performance over the baseline system, there were still almost twice as many unacceptable landings as satisfactory landings with the optimized system. These results indicated that the optimized system, while better than the baseline system, still had major deficiencies requiring improvement.

The properties of the two systems are shown in table 1, in the Test Item Description section above. The optimized system was identical to the baseline system until 100 feet AGL, when the longitudinal force gradient was increased to five times the baseline value over a one-second span. At 30 feet AGL, the spoilers were automatically retracted. See above for a discussion of the LAMARS testing that led to these changes.

The comparison of the optimized system with the baseline system was accomplished by alternating between the baseline and optimized systems during each test flight, as shown in appendix D. This methodology had the advantage of controlling for weather, turbulence, pilot proficiency, and variations in procedure between flight test engineers. Each pilot had approximately three flight hours for the comparison. For the first hour, each pilot proceeded with a build-up in workload flying the baseline system. For the second hour, each pilot proceeded with the same build-up flying the optimized system. For the third hour, only straight-in approaches were flown with zero crosswind, nominally alternating between two runs with the baseline system and two runs with the optimized system. Natural crosswinds were flown if it was determined that the TIFS was unable to reliably model crosswinds at the 185 knot approach speed.

Using the optimized system, the aircraft was much less sensitive in pitch, and was more capable of achieving a repeatable and predictable flare, even when entry conditions to the flare were varied. The optimized system required different flare timing than the baseline system. All three pilots, on their first approach with the optimized system, flared high. This difference in timing brought out the fact that the entire STAV approach was very reliant on open-loop technique rather than closed-loop flying down to touchdown, regardless of the feel system. The correction for leveling too high was an unnatural push, instead of a simple relaxation of longitudinal pull. This push was more noticeable with the increased inceptor force of the optimized system and increased the workload. This increase in workload led to at least one landing that achieved desired performance but was deemed to require improvement due to moderate workload. Performance improved with experience, as shown by the decrease of inadequate landings presented in figure F-4 in appendix F.

In smooth air, the optimized system was more conducive to Level 1 landings. The baseline system was sensitive, requiring extensive compensation leading to Level 2 landings, even when desired performance was achieved. In turbulence, the optimized system made it easier to compensate for glideslope deviations in the flare, but both systems required extensive compensation during the entire approach in the form of small, frequent inputs. In the absence of gusts, the optimized system could still be flown to Level 1 landings, even in moderate turbulence. The inceptor forces of the baseline system, however, were so light that moderate turbulence could cause the inertia of the pilot's hand to move the control, adding to the already considerable compensation required.

Figure F-8 in appendix F shows the difference in physical workload required by the two systems. In this figure, physical workload is quantified as a two-dimensional combination of aggressiveness and duty cycle that serves as a time-domain analog of the frequency-domain concept of "frequency content." Thus, large, abrupt, and frequent inceptor motion is plotted in the upper right corner and was analogous to "high pilot gain." Conversely, small, smooth, infrequent inceptor motion is plotted in the lower left corner and was related to "low pilot gain."

The wide range of aggressiveness for the baseline system indicated a lack of predictability, as a highly predictable system would have required the same aggressiveness on each approach. On average, the optimized system required roughly half the aggressiveness and a slight decrease in duty cycle compared to the baseline system. These quantitative descriptions correlated well with the pilots' comments of increased predictability and reduced workload when flying with the optimized system.

The difference in the two systems was most pronounced in the last 15 feet above simulated touchdown. The baseline system sensitivity prevented precise control and even led to mild, recognized pitch PIO as the distance to the runway decreased. The optimized system's increased inceptor forces allowed for more predictable control and for better perception and correction of small changes in pitch near touchdown. The baseline system's tendency to produce a sinking sensation at these low altitudes was not perceived with the optimized system.

Table F-1 in appendix F shows the performance for the inadequate landings. Many of the baseline system landings failed to meet adequate performance for more than one criterion, while

the optimized system tended to fail only one criterion at a time. Also, the optimized system landings showed no evidence of tail strikes, likely due to the increased inceptor force inhibiting the pilot from rapid pulls while close to the runway. Like the baseline system, the optimized system inadequate landings were often a trade-off between longitudinal displacement and sink rate, both of which relied on the longitudinal inceptor inputs in the flare.

PIO characteristics for the baseline system were all rated “1” except for two cases. In one instance, an overshoot in pitch correction at 10 feet AGL resulted in tight control leading to pitch oscillations that were not divergent, and a PIO rating of 4. In another instance, turbulence on final approach resulted in undesirable pitch motions (2-3 cycles) which tended to occur but did not affect task performance. No PIO tendencies were observed with the optimized system, as shown in figure F-9 in appendix F.

Like the baseline system, the optimized system required somewhat mechanical timing for reducing power and beginning the flare. The aircraft still had to be flown largely open-loop. An input was commanded, and then the pilot waited for the aircraft to respond to see what correction would be required, as with the baseline system. This lag in pitch response led to increased pilot workload for both systems. The inceptor sensitivity in the baseline system added to this workload.

The LAMARS optimized control system increased the inceptor force gradient at 100 feet AGL. Pilots preferred the higher inceptor gradient of the LAMARS optimized control system during the approach and landing phases, but the timing of the gradient shift was inappropriate. During simulator testing, the change in gradient at 100 feet AGL was not objectionable to the pilots, as very few inceptor inputs were required above this altitude. However, during flight testing, turbulence required frequent pilot inputs above 100 feet AGL. Pilots became accustomed to the required inceptor inputs above 100 feet AGL, and then the gradient changed, which required compensation. Pilots commented that it would have been desirable to have the same inceptor force gradient for the entire final approach. The timing of this inceptor force gradient change would be similar to another highly-augmented military aircraft, the F-16, which changes its flight control gains when the aircraft is configured to land. **Provide more time to acclimate to inceptor force gradient changes prior to touchdown. (R6)**

Roll inceptor gains did not change, which adversely affected control harmony. When testing in LAMARS, pilots required very few lateral corrections below 100 feet AGL. However, during flight test, turbulence and gusts required the pilot to make low altitude lateral corrections. The degraded control harmony decreased roll control predictability and led to over-controlling in the roll axis when pilots corrected for turbulence and gusts. **Change lateral inceptor forces to preserve control harmony on final approach. (R7)**

TIFS Simulation Flying Qualities Results

Programmed test inputs (PTI) and semi-open loop capture tasks were performed on downwind to determine the flying qualities of the TIFS simulation of the STAV flight control system. PTI included pitch doublets, steps and frequency sweeps, roll steps, and yaw doublets

and steps. Capture tasks included pitch, roll, and heading. The baseline system was in effect for all flying qualities maneuvers, as the optimized system did not engage until 100 feet AGL.

Figure F-10 in appendix F shows a time history of a pitch doublet and the STAV model pitch rate response. Table 7 shows the short period damping ratio and natural frequency as determined using the time ratio method due to the large damping ratio.

Figure F-11 in appendix F shows a time history of a yaw doublet and the STAV model angle of sideslip response. Table 7 shows the Dutch roll damping ratio and natural frequency as determined using the time ratio method due to the large damping ratio.

Table 7. Damping Ratio and Natural Frequency for TIFS/STAV

Mode	Damping Ratio	Natural Frequency
Short Period	0.78	2.12 rad/sec
Dutch Roll	0.80	1.11 rad/sec

Both the short period and Dutch roll damping ratios and natural frequencies were within the range of values considered satisfactory by MIL-STD 1797B. This information drove the test team to investigate other reasons for the poor STAV handling qualities.

Figure F-12 in appendix F shows a time history of a step and the STAV model flight path angle response. Initially, pitch steps were 2 seconds in duration before the pilot recovered. The pitch steps were extended to 5 seconds to account for the low frequency of the short period. The initial flight path response was in the opposite sense as the command and of small amplitude. After a delay of almost a second, the response began to follow the commanded sense and amplitude. This time delay in flight path response contributed to the unpredictability seen on approach and landing and led to the open-loop commands necessary for adequate landing performance.

During capture tasks up and away, the pitch and roll performance appeared responsive for an aircraft the size of the STAV. Yaw response was slower than pitch and roll, and was accompanied by a “heaving” feeling.

Pitch captures typically had 2-3 overshoots, and the final attitude was difficult to predict, given the lag in pitch response, especially with large pitch commands. The pitch capture results were consistent with the pitch lag and baseline system inceptor sensitivity that adversely affected the handling qualities on approach and landing.

Entering bank required approximately 5 pounds of forward inceptor force to maintain level flight, and rolling out required a 5 pound pull. Roll “ratcheting” at bank angles greater than 20 degrees was noted as a lateral heaving motion, as well as in g. Heading captures of 15 degrees with 15 to 20 degrees of bank resulted in 3 degrees of heading overshoot, but the aircraft would settle back 2 degrees after returning to wings level flight. The roll and heading behaviors were likely the result of a STAV flight control system feature that feeds in angle of attack with roll to assist with level turns. The roll and yaw capture tasks correlated well with the approach and landing handling qualities.

Overall, the TIFS followed the STAV model well. Figures F-13 and F-14 show the STAV model response in pitch in smooth air and turbulent air. Accurate model-following was seen by the similarity in shape and magnitude of the peaks. The accurate model-following illustrates that the STAV handling qualities can be determined using the TIFS.

CONCLUSIONS AND RECOMMENDATIONS

The HAVE STAV test team performed six test flights totaling ten flight hours during September 2007 to perform a limited handling qualities evaluation of the Supersonic Tailless Air Vehicle (STAV) model during powered approach and landing. The test team successfully accomplished all test objectives: determine the powered approach handling qualities of the baseline STAV model, compare the Large Amplitude Multi-mode Aerospace Research Simulator (LAMARS) optimized control system to the baseline STAV control system, and determine the flying qualities for the Total In-Flight Simulator (TIFS) simulation of the STAV flight control system.

The HAVE STAV test team determined the powered approach handling qualities of the baseline STAV model. Based on the assigned workload tasks, the baseline STAV model handling qualities were unacceptable during the flare and landing. When pilots achieved adequate performance for the landing task, the performance was not repeatable. The lack of a HUD increased pilot workload by forcing the pilot to crosscheck between the heads-down display and outside visual references. Projecting flight information displayed on a typical HUD would allow the pilot to have both flight information and visual references simultaneously, reducing the need for heads down time.

R1: Implement a HUD on the STAV. (page 13)

A HUD would present the current aircraft parameters to the pilot. However, due to the aircraft characteristics and overall system time delay, these parameters alone would not be sufficient for the pilot to predictably flare and land the aircraft. Combining the current aircraft parameters with predictive guidance information from a flight director or predictive flight path marker would increase the STAV flight predictably, particularly during flare and landing. Neither a flight director nor predictive flight path marker were used during testing.

R2: Implement predictive guidance on the STAV. (page 13)

The primary objectionable flight control characteristic during approach and landing of the baseline STAV model was pitch sensitivity. The light control forces required during the flare decreased predictability and increased pilot workload. Baseline inceptor gains were too low during approach and landing, resulting in a loose or light feel, objectionable inceptor sensitivity, and increased duty cycle and aggressiveness.

R3: Increase the inceptor force gradient for approach and landing. (page 13)

Vertical velocity at touch down was the critical parameter leading to unacceptable handling qualities. When the pilots focused on meeting the desired sink rate criterion, the landing distance degraded to adequate or inadequate. Contributing factors to this pilot tradeoff were flight response unpredictability and light control forces in the flare, which increased pilot workload and compensation.

Time delay in flight path response reduced the predictability of pitch inputs, resulting in open loop, mechanical pilot compensation for approach and landing. This compensation included power reductions at specific altitudes, flare initiations at specific altitudes, and step or impulse inputs followed by a pause to allow the aircraft to respond.

R4: Reduce the time delay in flight path response. (page 13)

Pilots noted lateral accelerations during roll. However, pilots did not consider this lateral acceleration to be objectionable when the pilot commanded the roll. When turbulence or gusts induced the roll, these lateral accelerations were more apparent, but were still not objectionable to the pilots. Pilots also noted roll sensitivity during turbulence.

Due to the design of the alpha-command controller, an upward pitching moment was experienced when rolling into a turn and a downward pitching moment when rolling out of a turn. These moments required the pilot to impart an unnatural push when rolling into a turn and an unnatural pull when rolling out of a turn.

R5: Reduce the amount of alpha compensation generated during turns. (page 14)

The LAMARS optimized control system improved task performance compared to the baseline STAV model. No simulated tail strikes occurred with the LAMARS optimized control system. However, the timing of the increase in inceptor forces in the optimized control system was objectionable.

R6: Provide more time to acclimate to inceptor force gradient changes prior to touchdown. (page 16)

Roll inceptor gains did not change, which adversely affected control harmony. The degraded control harmony decreased roll control predictability and led to over-controlling in the roll axis when pilots corrected for turbulence and gusts.

R7: Change lateral inceptor forces to preserve control harmony on final approach. (page 16)

The HAVE STAV test team determined the flying qualities for the TIFS simulation of the STAV flight control system. The TIFS simulation of the STAV flight control system accurately followed the model.

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LIST OF ACRONYMS AND SYMBOLS

AFIT	Air Force Institute of Technology
AFRL	Air Force Research Laboratory
AGL	Above Ground Level
CHR	Cooper-Harper Rating
HUD	Heads Up Display
KIAS	Knots Indicated Airspeed
LAMARS	Large Amplitude Multi-mode Aerospace Simulator
NGC	Northrop Grumman Corporation
PIO	Pilot In-the-loop Oscillation
PIOR	Pilot In-the-loop Oscillation Rating
STAV	Supersonic Tailless Air Vehicle
TIFS	Total In-Flight Simulator
TMP	Test Management Project
TPS	Test Pilot School
TW	Test Wing

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APPENDIX A. TOTAL IN FLIGHT SIMULATOR DETAILED DESCRIPTION

Calspan

Flight Research Group

TOTAL IN-FLIGHT SIMULATOR - TIFS

Introduction

The USAF Flight Dynamics Directorate Total In-Flight Simulator (TIFS) aircraft pictured in Figure 1 is an NC-131H (commercial Convair 580) twin turboprop transport modified as a six degree-of-freedom in-flight simulator. The TIFS aircraft is operated under a Cooperative Research and Development Agreement for the USAF by Calspan Corporation (Calspan) and is maintained and operated by Calspan's Flight Research Group in Buffalo, NY. Calspan was previously Veridian and more recently General Dynamics, Advanced Information Systems. The TIFS NC-131H aircraft provides in-flight simulation capabilities for advanced flying qualities and display research and is also used to demonstrate advanced flight control concepts and avionics systems to test pilots and engineers. The NC-131H aircraft also functions as an avionics flying test bed in a configuration separate from the in-flight simulator.

Figure 1 TOTAL IN-FLIGHT SIMULATOR (TIFS)

History

In-flight simulation has been used with great success for handling quality research and new aircraft development since the 1950s. The real world motion and visual cues, actual piloting tasks (e.g., navigation, approach to landing, and actual touchdowns) and associated stress levels, and realistic atmospheric turbulence are the primary benefits of in-flight simulation. In-flight simulators are excellent evaluation tools for new aircraft designs, flight control system research, cockpit display evaluations, pilot control inceptors, and test pilot training. An avionics flying test bed offers the same advantages for research and development of sensors and navigation systems.

The TIFS aircraft was developed in the late 1960's under Air Force Flight Dynamics Laboratory sponsorship. The Air Force objectives were to advance simulation technology for flying qualities research and to help develop new Air Force airplanes. The FAA, interested in simulating SuperSonic Transport (SST) landing visibility, also helped initiate the project. The Air Force furnished a C-131B as the basic airframe and Calspan performed the modifications to convert it into an in-flight simulator. Significant modifications included a separate simulation cockpit, additional control surfaces, computer-controlled hydraulic actuators, and turbo-prop engines. The final aircraft, designated an NC-131H, first flew in July 1970. The TIFS' turboprop engines and propellers were replaced in 1992 and 1994, respectively, providing better performance and maintainability.

In 1985, an avionics nose, which is interchangeable with the simulation cockpit, was developed. The TIFS systems test configuration is called the Avionics System Test and Training Aircraft (ASTTA). It hosts radar, infrared, and electro-optical detection systems as well as inertial navigation and a Global Positioning System (GPS). It is a highly instrumented flying test bed used to test tactical sensors and other avionics systems. The ASTTA is also a unique tool to train system designers, evaluators, and flight crew in airborne test techniques at a crew station installed in the aft cabin.

In 1998, extensive modifications were made to the TIFS simulation cockpit to accommodate test equipment for the eXternal Visibility System (XVS) program element of the NASA High Speed Research (HSR) program (Reference 1) and the Synthetic Vision (SV) component of the Aviation Safety Program (AvSP). TIFS was fitted with a new nose cap and canopy to increase the simulation cockpit volume to accommodate the XVS display system and a Collins X-band radar. The modified simulation cockpit is shown in Figure 2.

The TIFS aircraft has been used for many research and development programs during its history. Numerous handling qualities studies have been completed on the aircraft, leading to improvements in criteria, specifications, and the understanding of airplane-pilot interaction. TIFS supported the Space Shuttle Orbiters in several development and modification programs. Military airplane development programs such as the B-1, the B-2, Tacit Blue, the X-29 and the YF-23 have used TIFS' unique capabilities for flight control system development and training prior to first flight. Advanced commercial aircraft have also been developed using the TIFS aircraft. Several supersonic transport aircraft and "million-pound" aircraft configuration programs for NASA and industry have employed TIFS for configuration and control system development, as well as for visibility and sensor investigations. TIFS has been used for human factors experiments on instrumentation, displays, control feel, motion cueing, and passenger ride sensitivity. The ASTTA configuration of TIFS has been used for global positioning system (GPS), armament avionics, and remotely piloted vehicle (RPV) development programs. It has also served as a training platform for test pilots and engineers. The breadth of these programs illustrates the flexibility of the TIFS.

Aircraft Configuration

A Convair C-131B twin reciprocating engine transport was highly modified for the in-flight simulator mission and designated an NC-131H. The aircraft was converted to turboprop configuration, making it equivalent to the civilian CV-580. TIFS was equipped with a separate evaluation cockpit (forward and below the standard cockpit), high bandwidth electrohydraulic actuators, programmable feel systems, electro-mechanical servos for throttle control, additional control surfaces for 6 Degree-Of-Freedom (6-DOF) motion capability, programmable displays, and the onboard computers and electronics used for the variable stability system (VSS). The additional aerodynamic controls are all-moving Side-Force Surfaces (SFS) on the mid positions of the wings, and Direct Lift Flaps (DLF) which are outboard of the engine nacelles. These surfaces, the conventional C-131 flight control surfaces, the throttle servos, and the model-following system provide full 6-DOF control (rotational: pitch, roll and yaw; translational: normal, axial, and side forces) to completely duplicate the computed responses of the simulated aircraft. Figure 2 shows the layout of the TIFS aircraft for in-flight simulation.

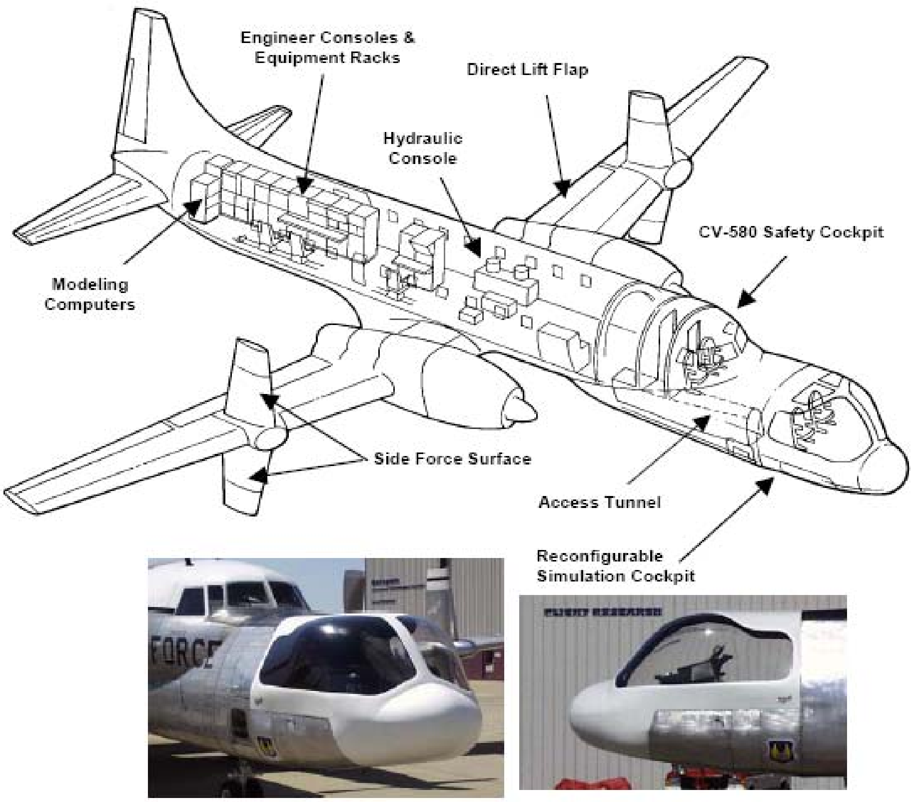


Figure 2: TIFS CONFIGURATION LAYOUT

Some of TIFS' features are listed below (Reference 2):

- Allison 501-D-22G turboprop engines (rated 4000 shaft horsepower)
- Strengthened structure to support the nose attachment, DLF, and SFS
- Separate hydraulic system for the variable stability system (40 gallons per minute flow rate at a pressure of 3000 pounds per square inch)
- Complete separate 2-place simulation cockpit attached to the nose, which is easily accessible for in-flight crew exchange
- Simulation flight deck can be tilted 7 degrees nose up
- Programmable Head-Down and Head-Up Displays (HDD & HUD) and CRT monitors
- Programmable feel systems, with multiple physical configurations available (wheel and column, centerstick, sidestick, rudder pedals, and servoed throttles)
- Large unobstructed-view canopy can be masked to duplicate external field-of-view
- Reconfigurable instrument panels and side consoles
- Large volume cockpit to accommodate custom avionics, radar, FLIR, and display packages
- Two Freon-Pack cooling systems for customer-supplied equipment
- Crew size: 8, including 2 safety pilots, 2 test engineers, and any combination of 4 customer evaluation pilots, engineers, or observers
- Capable of actual touchdowns with the simulation system engaged

VSS Characteristics

In-flight simulation is conducted using the VSS. The VSS is an electronic system using digital and analog computers with 1553B, ARINC 429, and ARINC 561 data bus interfaces. The VSS can be programmed directly in C, Ada, and FORTRAN languages, or symbolically using Matlab™ Simulink, which generates C code. This makes the VSS a useful tool for rapid prototyping and allows quick turnaround of desired system changes. The following computers are used by the VSS:

- Power PC computer with VxWorks for displays and modeling
- Digital Signal Processor (DSP)-based subsystem (installed in a Personal Computer (PC)-compatible host computer) for feel system, input/output management, and model-following control
- A host PC for communication with other systems, passing data to and from the DSPs, data recording, and real-time plotting.
- Analog patch panel for interface with sensors, model-following, feel systems, and simulation cockpit displays

The TIFS simulation system operates under a model-following concept (Figure 3) to provide 6 DOF simulation capability. Evaluation pilot controller activity is transferred to the onboard Silicon Graphics computer which calculates the modeled aircraft's equations-of-motion in real-time. Model responses are based on pilot inputs, the modeled flight control system, and real or simulated sensor inputs and atmospheric flight conditions. The calculated model responses, along with TIFS motion sensor signals, generate feedforward and response error signals in an explicit model-following simulation system programmed in a DSP. The TIFS

model-following control laws command the TIFS control surfaces, and thus produce TIFS motions at the evaluation pilot station which accurately match the corresponding model motion variables. The six TIFS controllers – ailerons, rudder, elevator, throttle, SFS, and DLF – provide independent control of all six degrees-of-freedom. The VSS commands control surface motions by sending electric signals to the electrohydraulic servos at the elevator, ailerons, rudder, DLF, and SFS. Electromechanical servos control the throttle and propeller pitch for the constant-speed turboprop engines.

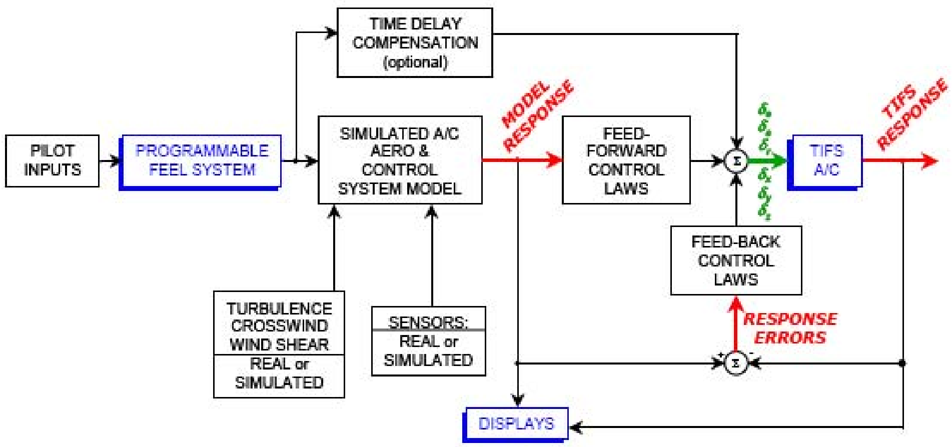


Figure 3 MODEL-FOLLOWING CONTROL LAW CONCEPT

The TIFS model-following control laws can include time delay compensation to effectively quicken the TIFS response. The resulting response from pilot command to TIFS motion has an overall time delay of 60 to 100 milliseconds, which is equivalent to lags present in most transport-class aircraft. Time delay can be increased to simulate an aircraft with excessive time delay. Through the model-following concept, the VSS provides high fidelity motion and visual cue reproduction of the simulated aircraft up to the control power and safe maneuvering limits of the NC-131H aircraft.

A summary of the TIFS flight envelope with the VSS engaged is presented below:

• Maximum airspeed:	270 KIAS
• Touchdown airspeed:	115 to 165 KIAS
• Steep approach capability:	-17 degrees flight path angle at 270 kts
• Maximum touchdown sink rate:	10 feet per second
• Maximum rate of climb:	2000 feet per minute
• Normal load factor limits:	+0.3 to +2.2 gs
• Lateral acceleration, N_Y:	± 0.25 g
• Altitude:	0 to 12,000 feet (including runway touchdown)
• Maximum Flight Duration:	2 to 3 hours (depending on installed equipment)

Safety Aspects

The standard NC-131H cockpit is occupied by two safety pilots who continuously monitor the simulation and aircraft systems. The safety pilots' control columns, rudder pedals, and throttle levers remain connected by the original mechanical (cable-driven) connections to the control surfaces and engine throttle. The safety pilots have the capability for "on-demand," manual, in-flight simulation disengage. Since the elevator, aileron, rudder, and throttle controls are always connected, the safety pilots can readily monitor the control activity while the VSS is engaged. When the VSS is disengaged they can immediately assume conventional control of the aircraft.

A variety of automatic and manual "safety trips" return the basic NC-131H mechanical controls to the safety pilots if maximum simulation operating limits are approached. Automatic safety trips will disengage the VSS to provide protection against exceeding the simulation operating envelope and/or over-stressing the airframe. The VSS monitors aircraft state (e.g., airspeed, normal acceleration, side acceleration, angle-of-attack, etc.), structural limits (horizontal or vertical tail loads, etc.), and control surface position error signals and will disengage if one of these signals exceeds a preset limit. When a safety trip occurs, control of the TIFS reverts back to the safety pilots without significant delay. In addition, each control surface actuator is equipped with relief valves to limit the hinge moments on a given surface. The safety pilots can also manually disengage the VSS and limit excursions of the aircraft which could result in aircraft damage. The safety pilots may disengage the simulation using VSS disengage switches on their control wheels and the throttle handles. The evaluation pilots may also disengage the VSS using switches on the evaluation control wheel or stick. Test engineers in the aft cabin can also disengage the VSS.

VSS Control

Controls for the VSS are located in the safety cockpit and at the test engineers' consoles in the main cabin. VSS engagement is controlled by the safety pilots from the VSS Control Panel, located on the pedestal in the safety cockpit. The test engineers control the VSS, data acquisition, and recording. Test engineer consoles provide for real-time model changes to the simulation flight control system, control feel, aerodynamic model, displays, and sensors, and allow real-time monitoring of test data.

The model-following system uses aircraft state feedback signals from various sources on the aircraft. Numerous other parameters are used for model validation and data recording. A CG-mounted sensor platform contains three-axis rate gyro and linear accelerometer packages, and an AN/ASN-50 attitude and heading reference system. A two-axis linear accelerometer in the evaluation cockpit measures pilot station Nz and Ny. Angular rates (p, q, r) are determined from the three-axis rate gyro. An Inertial Navigation System (INS), LTN-72R, provides aircraft attitudes (pitch, roll, and yaw), inertial position, and inertial velocity. Earth-axis position and velocity information is available using differential GPS. Aerodynamic angle-of-attack (AOA) and angle-of-sideslip (AOS) are measured by vanes located on the sides and bottom of the evaluation cockpit, respectively. TIFS is equipped with a standard aircraft static pressure port, pitot probe, and air temperature bulb. Dedicated static ports were installed for the VSS. An inertially-compensated air data computer uses these sources to provide altitude, altitude rate, indicated airspeed, true airspeed, airspeed rate, and Mach number. Computational techniques are used to obtain inertial AOA and AOS, and their associated derivatives, inertial AOA rate and inertial AOS rate. Gust information is obtained from comparisons of inertial and aerodynamic AOA and AOS. Complementary filters are used to blend the slower, heavily filtered, pressure-derived data with the high-frequency inertial data. A radar altimeter is used for height above ground and descent rate information during approach and landing evaluations. An additional capability of the VSS is that the TIFS onboard sensors, customer-supplied sensors, or simulated sensors can be interfaced with the simulation model.

The VSS can be programmed to provide a wide range of aircraft characteristics within its flight envelope. The TIFS flight envelope and capabilities have made it an ideal choice for modeling approach and landing conditions when matching speeds exactly with the modeled configuration. However, the models that can be simulated are applicable to aircraft with flight envelopes much larger than the envelope of the NC-131H because of TIFS' high-fidelity motion capability. TIFS will match time histories of the dynamic parameters (Nz, Ny, p, q, etc.) which are most important for piloted evaluations (Reference 5) even when operating with a speed mismatch. The capability to simulate sensors and displays enhances this feature. The 6-DOF motion capability allows the TIFS to simulate the flight characteristics and geometry of virtually any aircraft (e.g., YF-23 fighter, 300-foot long SST, B-2 bomber, Space Shuttle). TIFS can also accurately model structural dynamics effects at the pilot station (up to approximately 3 Hertz) in addition to rigid body aerodynamic characteristics if the customer-supplied model

includes these aeroelastic effects (Reference 6). The TIFS actuators generate high frequency motion that can match model dynamics up to 20 radians per second.

The details of VSS capabilities for modeling all of the aircraft dynamic characteristics are not easily generalized and are beyond the scope of this document. Additional details may be found in References 5 through 11. Example time history comparisons of flight test data with simulation model data demonstrating TIFS' model quality are shown in Figures 4 and 5.

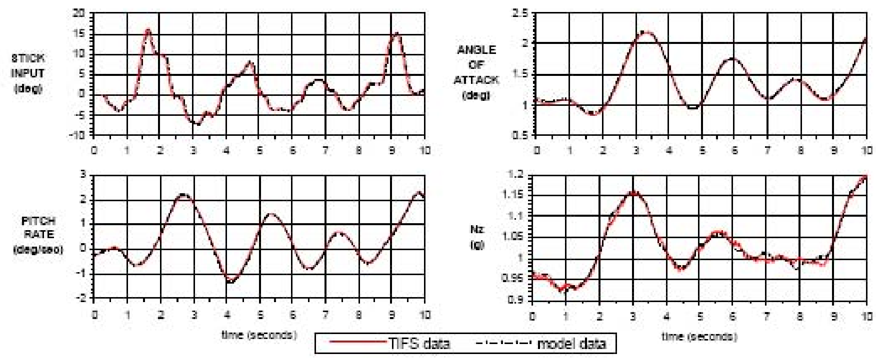


Figure 4 EXAMPLE TIME HISTORY MATCH - PITCH AXIS

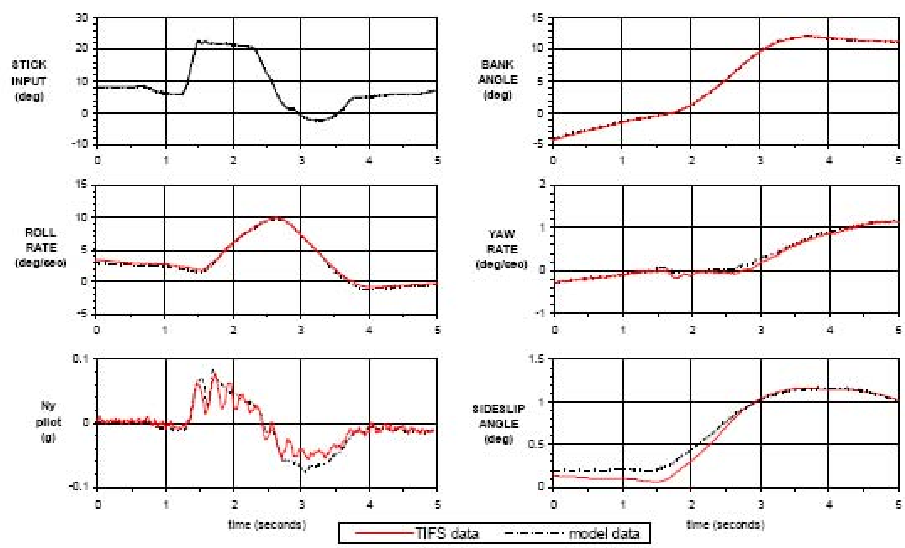


Figure 5 EXAMPLE TIME HISTORY MATCH - ROLL & YAW AXES

Feel Systems

The TIFS variable feel systems also utilize a model-following system and are fully programmable to provide a wide range of controller characteristics. Each feel system axis is controlled by a DSP-based multi-function Industry Standard Architecture (ISA) card installed in the feel system model-following computer. The variable feel system can be programmed directly in the C computer language, or symbolically using Matlab™ Simulink, which generates C code. The VSS calculates the feel system feedback as well as the model-following feedforward commands. For each axis, the model position, rate, and acceleration signals are combined to form commands to the 25 rad/sec first-order hydraulic servos which move the cockpit controls to follow the feel system model positions.

The variable feel system is capable of modeling a wide range of static and dynamic control characteristics including frequency, damping, linear/nonlinear gradients, breakout, friction, hysteresis, soft/hard stops, and bobweight and downspring effects. The feel system can also simulate and modulate any linear or nonlinear characteristics which are designed in the model flight control system, such as dynamic pressure scheduling, configuration and mode changes, autopilot and autothrottle backdrive, lead/lag compen-sation, transport delay, and envelope protection/limiting. TIFS can be configured with several types of cockpit controls including wheel and column, centerstick, sidestick, rudder pedals, and throttles (Figure 6). The throttle handles can be operated with mechanical friction only, or using a fully programmable feel system. TIFS also has provisions to accept customer-supplied controllers for evaluation (References 7 and 9). Both pilot force and feel servo position can be used as inputs to the simulated aircraft model.

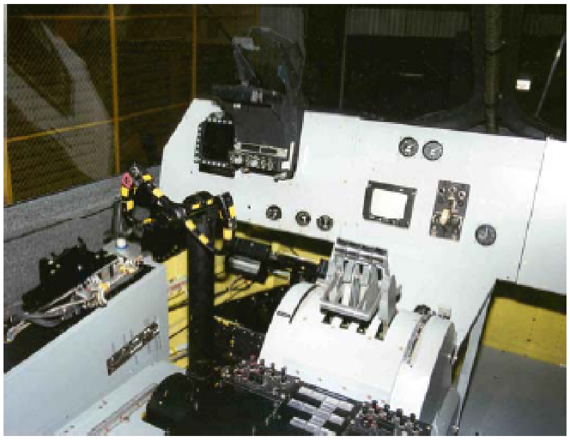


Figure 6 TIFS VARIABLE FEEL WHEEL COLUMN, SIDESTICK, RUDDER PEDALS, AND THROTTLES

Design specifications for the variable controllers are outlined in Tables 1, 2, and 3. The values in these tables do not represent limitations of the TIFS variable feel system but values which Calspan considers the maximum typically used for an aircraft. Selected values can be

exceeded for specific customer-supplied model requirements. The values serve to illustrate the range of characteristics which can be modeled.

Table 1
TIFS VARIABLE FEEL WHEEL AND COLUMN SPECIFICATIONS

Parameter	Column	Wheel	Pedals*
Maximum force output (lbs)	100	100	200
Force gradient **	1 to ∞ lb/in	0.1 to ∞ lb/deg	4 to ∞ lb/in
Damping ratio	-0.5 to 2.0	-0.5 to 2.0	-0.5 to 2.0
Natural frequency (rad/sec)	0 to 50	0 to 50	0 to 50
Breakout range (lbs)	0 to 100	0 to 100	0 to 200
Hysteresis (lbs)	0 to 100	0 to 100	0 to 200
Control travel range	12 in total	± 95 deg	± 3.5 in
Dead band range	from zero up to maximum control travel range		

* The rudder pedal characteristics remain the same for all three pitch / roll inceptor configurations.
** Infinite gradient is limited by maximum force output capability and simulates a fixed controller.

Table 2
TIFS VARIABLE FEEL CENTERSTICK SPECIFICATIONS*

Parameter	Pitch	Roll
Maximum force output (lbs)	35	35
Force gradient **	0.1 to ∞ lb/deg	0.1 to ∞ lb/deg
Damping ratio	-0.5 to 2.0	-0.5 to 2.0
Natural frequency (rad/sec)	0 to 50	0 to 50
Breakout range (lbs)	0 to 35	0 to 35
Hysteresis (lbs)	0 to 35	0 to 35
Control travel range (degrees)	± 30	± 30
Dead band range	from zero up to maximum control travel range	

* Pitch/roll pivot distance is a coincident 9 inches from the grip reference point.
** Infinite gradient is limited by maximum force output capability and simulates a fixed controller.

Table 3
TIFS VARIABLE FEEL SIDESTICK SPECIFICATIONS*

Parameter	Pitch	Roll
Maximum force output (lbs)	50	50
Force gradient **	0.05 to ∞ lb/deg	0.05 to ∞ lb/deg
Damping ratio	-0.5 to 2.0	-0.5 to 2.0
Natural frequency (rad/sec)	0 to 50	0 to 50
Breakout range (lbs)	0 to 50	0 to 50
Hysteresis (lbs)	0 to 50	0 to 50
Control travel range (degrees)	± 30	± 30
Dead band range	from zero up to maximum control travel range	

* Pitch/roll pivot distance is a coincident 7 inches from the grip reference point.
** Infinite gradient is limited by maximum force output capability and simulates a fixed controller.

As mentioned earlier, the VSS characteristics (simulated aircraft dynamics, variable feel controller characteristics, etc.) are controlled by the test engineers at the main cabin

consoles. VSS can only be engaged by the safety pilot after the evaluation pilot has engaged the feel system.

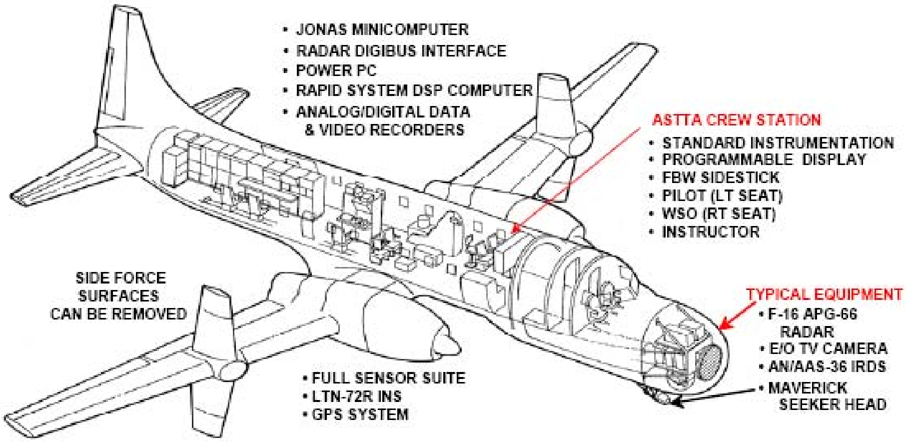
ASTTA Configuration

The ASTTA is the avionics test bed configuration of the TIFS. The ASTTA features a large capacity avionics compartment in a separate interchangeable nose attached in place of the evaluation cockpit. The avionics nose can accommodate 1,000 to 1,500 pounds of customer-supplied equipment such as large prototype radars, infrared cameras, and other sensors. The compartment is seven feet in diameter and six feet deep. The ASTTA nose has had the following equipment installed for various programs:

- AN/APG-66 digital fire control radar (used on the F-16), with air-to-air and ground mapping modes
- AN/AAS-36 slewable infrared detection system (IRDS) turret is interchangeable with electro-optical (E-O) imaging system TV camera
- Maverick missile seeker (AGM-65A), with seeker video on a panel display
- LTN-72R inertial navigation system with automatic radio position update
- Millimeter wave (35GHz) radar

Located in main cabin, the ASTTA crew station features a variable feel sidestick and throttle, programmable displays and controls for FLIR, radar, and standard instrumentation, and seating for a pilot, Weapons System Operator (WSO), and instructor. The ASTTA crew-station cockpit in the main cabin also provides fly-by-wire simulation capability. The system operator-engineer's console contains video and data recorders, a mini-computer with real-time interface to the radar data bus, and cooling system controls. Figure 7 shows the ASTTA configuration layout.

The ASTTA is a versatile test bed aircraft with capabilities suited to both the development of avionics systems and to the training of designers, engineers, and test pilots in airborne test techniques. The aircraft offers the unique capability to operate and test avionics systems separately or in an integrated fashion quickly and inexpensively. The capability to test the human interface with the systems in the appropriate flight environment is the strength of ASTTA. In addition to training programs at the US Air Force and Naval Test Pilot Schools, the ASTTA configuration of TIFS has also been used in an RPV program and a Smart Weapons (cruise missile) program. More detailed information about ASTTA can be found in Reference 12.



ASTTA CREW STATION

ASTTA NOSE

Figure 7: ASTTA CONFIGURATION LAYOUT

Data Recording

The TIFS aircraft is equipped with onboard systems for recording test data. Data acquisition is controlled by the PC host computer interface at the test engineer consoles. Up to 512 channels of digital data may be recorded directly from the PowerPC or DSP computers and stored on hard disk, a 230 Megabyte Bernoulli cartridge, or a JAZ drive. Digital information is available through MIL-STD-1553B, ARINC 429, and ARINC 561 data bus interfaces. Selected parameters may be directed to the test engineers' computer displays as well as the six-channel strip chart brush recorder located at the test engineer console for real-time monitoring. Audio and video information (from cameras, displays, and crew voices) is also recorded onboard using three VCRs and two audio cassette tape recorders. The aircraft also has provisions for telemetry transmission of data, audio, and video signals.

Future Activities

The TIFS NC-131H is a unique and valuable national asset that provides six degree-of-freedom in-flight simulation capabilities for research, development, training, and risk reduction for new aircraft and systems development. TIFS continues to demonstrate its flexibility in more recent projects combining display, flight controls, and handling qualities research and development. TIFS is also used to demonstrate advanced flight control system concepts to test pilots and engineers. The ASTTA configuration also provides unique capabilities as an avionics systems training platform and flying test bed. Near-term future programs for TIFS include further development of external visualization displays and controls for advanced aircraft, development of control and avionics related to uninhabited aerial vehicles (UAVs), flying test bed for advanced sensors and radars, and continued research into handling qualities and pilot-induced oscillation (PIO).

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APPENDIX B.   LAMARS MODELING AND SIMULATION

Table B-1. LAMARS Test Matrix

Key of Abbreviations in Modeling and Simulation Matrix			
Pilot		**Task**	
1	Speares	N	Normal
2	Domsalla	L	Lateral Offset
3	Quashnock	V	Vertical Offset
Control Type		**Feel System**	
A	Alpha	B	Baseline
G	Gamma	IS	Inc Inceptor Force
P	Pitch Rate	SP	Spoiler Reset
		IS/SP	Combined
Crosswind		**Airspeed**	
O	Zero	L	175
M	Max	H	195

Hour #	Pilot	Run #	Control Type	Feel System	Airspeed	Task	Crosswind
1	1	1	A	B	L	N	O
1	1	2	A	B	L	N	O
1	1	3	A	B	L	N	O
1	1	4	A	B	L	N	M
1	1	5	A	B	L	L	O
1	1	6	A	B	L	L	M
1	1	7	A	B	H	N	O
1	1	8	A	B	H	N	M
1	1	9	A	B	H	L	O
1	1	10	A	B	H	L	M
2	1	1	G	B	L	N	O
2	1	2	G	B	L	L	M
2	1	3	G	B	H	N	O
2	1	4	G	B	H	L	M
2	1	5	P	B	L	N	O
2	1	6	P	B	L	L	M
2	1	7	P	B	H	N	O
2	1	8	P	B	H	L	M
2	1	9	A	B	L	V	O
2	1	10	A	B	L	V	M
3	2	1	A	B	L	N	O
3	2	2	A	B	L	N	O
3	2	3	A	B	L	N	O
3	2	4	A	B	L	N	M
3	2	5	A	B	L	L	O
3	2	6	A	B	L	L	M
3	2	7	A	B	H	N	O
3	2	8	A	B	H	N	M
3	2	9	A	B	H	L	O
3	2	10	A	B	H	L	M

Table B-1. LAMARS Test Matrix (Continued)

Hour #	Pilot	Run #	Control Type	Feel System	Airspeed	Task	Crosswind
4	2	1	G	B	L	N	O
4	2	2	G	B	L	L	M
4	2	3	G	B	H	N	O
4	2	4	G	B	H	L	M
4	2	5	P	B	L	N	O
4	2	6	P	B	L	L	M
4	2	7	P	B	H	N	O
4	2	8	P	B	H	L	M
4	2	9	A	B	H	V	O
4	2	10	A	B	H	V	M
5	3	1	A	B	L	N	O
5	3	2	A	B	L	N	O
5	3	3	A	B	L	N	O
5	3	4	A	B	L	N	M
5	3	5	A	B	L	L	O
5	3	6	A	B	L	L	M
5	3	7	A	B	H	N	O
5	3	8	A	B	H	N	M
5	3	9	A	B	H	L	O
5	3	10	A	B	H	L	M
6	3	1	G	B	L	N	O
6	3	2	G	B	L	L	M
6	3	3	G	B	H	N	O
6	3	4	G	B	H	L	M
6	3	5	P	B	L	N	O
6	3	6	P	B	L	L	M
6	3	7	P	B	H	N	O
6	3	8	P	B	H	L	M
6	3	9	A	B	L/H	V	O
6	3	10	A	B	L/H	V	M
7	1	1	A	IS	L/H	N	O
7	1	2	A	IS	L/H	N	M
7	1	3	A	IS	L/H	L	O
7	1	4	A	IS	L/H	L	M
7	1	5	A	IS	L/H	N	O
7	1	6	A	IS	L/H	N	M
7	1	7	A	IS	L/H	L	O
7	1	8	A	IS	L/H	L	M
7	1	9	A	IS	L/H	N	O
7	1	10	A	IS	L/H	L	M
8	2	1	A	IS	L/H	N	O
8	2	2	A	IS	L/H	N	M
8	2	3	A	IS	L/H	L	O
8	2	4	A	IS	L/H	L	M
8	2	5	A	IS	L/H	N	O
8	2	6	A	IS	L/H	N	M
8	2	7	A	IS	L/H	L	O
8	2	8	A	IS	L/H	L	M
8	2	9	A	SP	L/H	N	O
8	2	10	A	SP	L/H	L	M

Table B-1. LAMARS Test Matrix (Continued)

Hour #	Pilot	Run #	Control Type	Feel System	Airspeed	Task	Crosswind
9	3	1	A	IS	L/H	N	O
9	3	2	A	IS	L/H	N	M
9	3	3	A	IS	L/H	L	O
9	3	4	A	IS	L/H	L	M
9	3	5	A	SP	L/H	N	O
9	3	6	A	SP	L/H	N	M
9	3	7	A	SP	L/H	L	O
9	3	8	A	SP	L/H	L	M
9	3	9	A	SP	L/H	N	O
9	3	10	A	SP	L/H	L	M
10	1	1	A	B	L	N	O
10	1	2	A	SP	L/H	N	O
10	1	3	A	SP	L/H	N	M
10	1	4	A	SP	L/H	L	O
10	1	5	A	SP	L/H	L	M
10	1	6	A	IS/SP	L/H	N	O
10	1	7	A	IS/SP	L/H	N	M
10	1	8	A	IS/SP	L/H	L	O
10	1	9	A	IS/SP	L/H	L	M
10	1	10	G/P	IS/SP	L/H	N	O
11	2	1	A	B	L	N	O
11	2	2	A	SP	L/H	N	O
11	2	3	A	SP	L/H	N	M
11	2	4	A	SP	L/H	L	O
11	2	5	A	SP	L/H	L	M
11	2	6	A	IS/SP	L/H	N	O
11	2	7	A	IS/SP	L/H	N	M
11	2	8	A	IS/SP	L/H	L	O
11	2	9	A	IS/SP	L/H	L	M
11	2	10	G/P	IS/SP	L/H	N	O
12	3	1	A	B	L	N	O
12	3	2	A	IS/SP	L/H	N	O
12	3	3	A	IS/SP	L/H	N	M
12	3	4	A	IS/SP	L/H	L	O
12	3	5	A	IS/SP	L/H	L	M
12	3	6	G	IS/SP	L/H	N	O
12	3	7	G	IS/SP	L/H	L	M
12	3	8	P	IS/SP	L/H	N	O
12	3	9	P	IS/SP	L/H	L	M
12	3	10	G/P	IS/SP	L/H	N	M
13	4	1	A	B	L	N	O
13	4	2	A	B	L/H	N	O
13	4	3	A	B	L/H	N	M
13	4	4	A	B	L/H	L	O
13	4	5	A	B	L/H	L	M
13	4	6	A	IS/SP	L/H	N	O
13	4	7	A	IS/SP	L/H	N	M
13	4	8	A	IS/SP	L/H	L	O
13	4	9	A	IS/SP	L/H	L	M
13	4	10	G/P	IS/SP	L/H	N	O

Table B-1. LAMARS Test Matrix (Continued)

Hour #	Pilot	Run #	Control Type	Feel System	Airspeed	Task	Crosswind
14	1	1	A	IS/SP	L	V	O
14	1	2	A	IS/SP	L	V	M
14	1	3	A	IS/SP	H	V	O
14	1	4	A	IS/SP	H	V	M
14	1	5	G	IS/SP	L	V	O
14	1	6	G	IS/SP	H	V	O
14	1	7	G	IS/SP	L/H	V	M
14	1	8	P	IS/SP	L	V	O
14	1	9	P	IS/SP	H	V	O
14	1	10	P	IS/SP	L/H	V	M
15	2	1	A	IS/SP	L	V	O
15	2	2	A	IS/SP	L	V	M
15	2	3	A	IS/SP	H	V	O
15	2	4	A	IS/SP	H	V	M
15	2	5	G	IS/SP	L	V	O
15	2	6	G	IS/SP	H	V	O
15	2	7	G	IS/SP	L/H	V	M
15	2	8	P	IS/SP	L	V	O
15	2	9	P	IS/SP	H	V	O
15	2	10	P	IS/SP	L/H	V	M
16	3	1	A	IS/SP	L	V	O
16	3	2	A	IS/SP	L	V	M
16	3	3	A	IS/SP	H	V	O
16	3	4	A	IS/SP	H	V	M
16	3	5	G	IS/SP	L	V	O
16	3	6	G	IS/SP	H	V	O
16	3	7	G	IS/SP	L/H	V	M
16	3	8	P	IS/SP	L	V	O
16	3	9	P	IS/SP	H	V	O
16	3	10	P	IS/SP	L/H	V	M
17	Neff	1	A	B	L/H	N	O
17	Neff	2	A	B	L/H	L	O
17	Neff	3	A	B	L/H	L	M
17	Neff	4	A	IS/SP	L/H	N	O
17	Neff	5	A	IS/SP	L/H	L	O
17	Neff	6	A	IS/SP	L/H	L	M
17	Cook	1	A	B	L/H	N	O
17	Cook	2	A	B	L/H	L	O
17	Cook	3	A	B	L/H	L	M
17	Cook	4	A	IS/SP	L/H	N	O
18	Cook	5	A	IS/SP	L/H	L	O
18	Cook	6	A	IS/SP	L/H	L	M
18	Porter	1	A	B	L/H	N	O
18	Porter	2	A	B	L/H	L	O
18	Porter	3	A	B	L/H	L	M
18	Porter	4	A	IS/SP	L/H	N	O
18	Porter	5	A	IS/SP	L/H	L	O
18	Porter	6	A	IS/SP	L/H	L	M

APPENDIX C. FLIGHT TEST MANEUVERS

PROGRAMMED TEST INPUTS AND SEMI-CLOSED LOOP TASKS

When the aircraft was on the downwind leg, at approximately 1500 feet AGL, the evaluator pilot took control of the aircraft and performed a series of programmed test inputs and semi-closed loop tasks. These inputs included steps and doublets in the pitch and yaw axes, as well as a step in the roll axis. The pilot recovered the aircraft to level flight after directed by the Calspan engineer in the back of the aircraft. The pilot then performed low gain capture tasks in pitch, roll, and heading. All maneuvers and programmed test inputs were repeated with the spoilers completely retracted, and a set of pitch steps were accomplished while the spoilers were being retracted.

PRECISION APPROACH AND LATERAL OFFSETS

For all approaches, the Total In-Flight Simulator generated a 2.5 degree glide slope that aimed at a point 750 feet long of the runway threshold. This point was chosen to provide sufficient safety clearance with a road that crossed perpendicular to the runway just prior to the overrun. This provided a ground distance of approximately 750 feet to flare before the planned touchdown point. The desired aim point and touchdown point are shown in figure C-1.

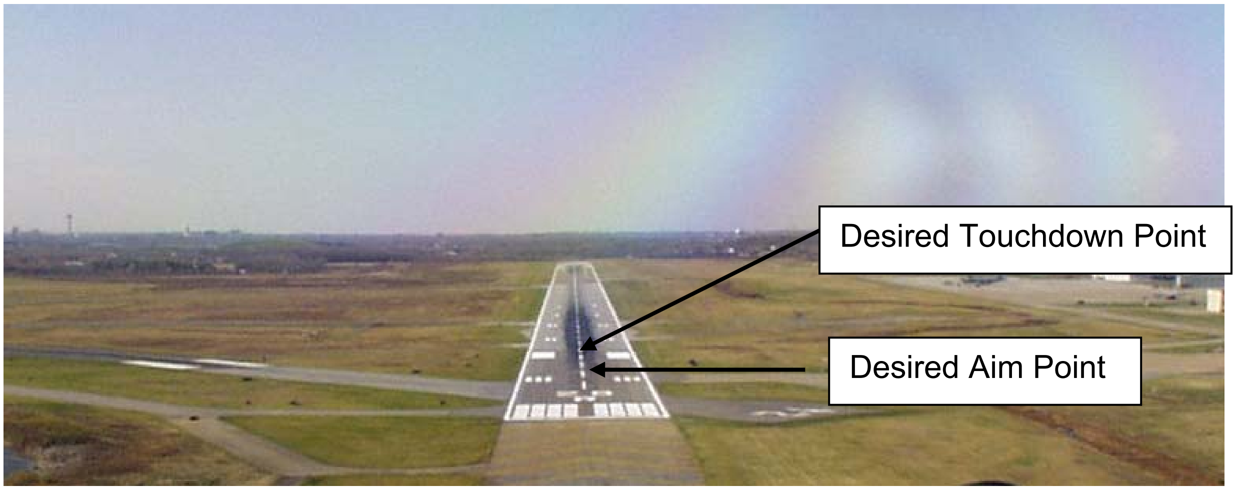

Figure C-1. Desired Aim Point and Touchdown Point

For all tasks requiring crosswinds, the TIFS side force generators were used to simulate a crosswind. The TIFS briefed capabilities stated that the side force generators could negate up to a 15 knot actual crosswind, or add to the actual crosswinds to generate the effect of a 15 knot crosswind. During flight testing, the test team found that when TIFS generated an effective crosswind greater than seven knots, the variable stability system was prone to nuisance systems trips with normal pilot inputs. These trips were due to the hinge forces generated by the side force controllers at a nominal approach speed of 185 knots. Therefore, TIFS was used to generate or eliminate a maximum crosswind of seven knots.

For normal landing tasks, the 2.5 degree glide slope was aligned with the centerline. For the lateral offset tasks, the glide slope was offset by 200 feet from centerline, as shown in figure C-2. It could be offset either right of left, based on the lateral correction direction dictated by the actual crosswinds. In the cockpit, the glideslope presentation to the pilot indicated on course when the pilot was lined up on the 200 foot lateral offset point. At 300 feet AGL, the test conductor called "maneuver", and the pilot aggressively maneuvered back to the centerline for the lateral offset tasks, in an effort to land at the desired touchdown point, which remained the same as the normal landing task. The approach airspeed was 185 knots in all cases.

Figure C-2. Lateral Offset Points

For the lateral offset tasks, the crosswinds were generated from the direction opposite of the offset, which increased the task difficulty by forcing the pilot to correct into the crosswind.

APPENDIX D. TIFS FLIGHT TEST MATRIX

Following the simulator testing in the Large Amplitude Multimode Aerospace Simulator (LAMARS), the conditions that warranted further evaluation were selected for flight testing in the Total In-Flight Simulator (TIFS). The matrix below shows the actual flight test runs.

Table D-1. TIFS Flight Test Matrix

Key of Abbreviations in Modeling and Simulation Matrix			
Pilot		**Task**	
1	Speares	N	Normal
2	Domsalla	L	Lateral Offset
3	Quashnock	(P)	Practice
Feel System		**Feel System**	
B	Baseline	O	LAMARS Optimized

Hour #	Pilot	Required to Meet Objective	Control Type	Feel System	Approach Airspeed	Task	Crosswind
1-1	1	1,2 and 3	Alpha	B	185 KIAS	N(P)	0
1-2	1	1,2 and 3	Alpha	B	185 KIAS	N	0
1-3	1	1,2 and 3	Alpha	B	185 KIAS	N	7
1-4	1	1,2 and 3	Alpha	B	185 KIAS	L(P)	0
1-5	1	1,2 and 3	Alpha	B	185 KIAS	L	0
2-1	1	1,2 and 3	Alpha	B	185 KIAS	L	7
2-2	1	2 and 3	Alpha	O	185 KIAS	N(P)	0
2-3	1	2 and 3	Alpha	O	185 KIAS	N	0
2-4	1	2 and 3	Alpha	O	185 KIAS	N	7
2-5	1	2 and 3	Alpha	O	185 KIAS	L(P)	0
2-6	1	2 and 3	Alpha	O	185 KIAS	L	0
2-7	1	2 and 3	Alpha	O	185 KIAS	L	7
2-8	1	2 and 3	Alpha	O	185 KIAS	N	7
3-1	2	1,2 and 3	Alpha	B	185 KIAS	N(P)	0
3-2	2	1,2 and 3	Alpha	B	185 KIAS	N	0
3-3	2	1,2 and 3	Alpha	B	185 KIAS	N	7
3-4	2	1,2 and 3	Alpha	B	185 KIAS	L(P)	0
3-5	2	1,2 and 3	Alpha	B	185 KIAS	L	0
4-1	2	2 and 3	Alpha	O	185 KIAS	N(P)	0
4-2	2	2 and 3	Alpha	O	185 KIAS	N	0
4-3	2	2 and 3	Alpha	O	185 KIAS	N	7
4-4	2	2 and 3	Alpha	O	185 KIAS	L(P)	0
4-5	2	2 and 3	Alpha	O	185 KIAS	L	0
4-6	2	2 and 3	Alpha	O	185 KIAS	L	7
4-7	2	1,2 and 3	Alpha	B	185 KIAS	L	7
5-1	3	1,2 and 3	Alpha	B	185 KIAS	N(P)	0
5-2	3	1,2 and 3	Alpha	B	185 KIAS	N	0
5-3	3	1,2 and 3	Alpha	B	185 KIAS	N	7
5-4	3	1,2 and 3	Alpha	B	185 KIAS	L(P)	0
5-5	3	1,2 and 3	Alpha	B	185 KIAS	L	0
5-6	3	1,2 and 3	Alpha	B	185 KIAS	L	7

Table D-1. TIFS Flight Test Matrix (Continued)

Hour #	Pilot	Required to Meet Objective	Control Type	Feel System	Approach Airspeed	Task	Crosswind
6-1	3	2 and 3	Alpha	O	185 KIAS	N(P)	0
6-2	3	2 and 3	Alpha	O	185 KIAS	N	0
6-3	3	2 and 3	Alpha	O	185 KIAS	N	7
6-4	3	2 and 3	Alpha	O	185 KIAS	L(P)	0
6-5	3	2 and 3	Alpha	O	185 KIAS	L	0
6-6	3	2 and 3	Alpha	O	185 KIAS	L	7
6-7	3	N/A	Alpha	B	185 KIAS	N	0
7-1	3	N/A	Alpha	B	185 KIAS	N	0
7-2	1	N/A	Alpha	B	185 KIAS	N	0
7-3	1	N/A	Alpha	B	185 KIAS	N	0
7-4	1	N/A	Alpha	O	185 KIAS	N	0
7-5	1	N/A	Alpha	O	185 KIAS	N	0
7-6	1	N/A	Alpha	B	185 KIAS	N	0
7-7	1	N/A	Alpha	B	185 KIAS	N	0
7-8	1	N/A	Alpha	O	185 KIAS	N	0
8-1	2	N/A	Alpha	B	185 KIAS	N	0
8-2	2	N/A	Alpha	B	185 KIAS	N	0
8-3	2	N/A	Alpha	O	185 KIAS	N	0
8-4	2	N/A	Alpha	O	185 KIAS	N	0
8-5	2	N/A	Alpha	B	185 KIAS	N	0
8-6	2	N/A	Alpha	B	185 KIAS	N	0
8-7	2	N/A	Alpha	O	185 KIAS	N	0
8-8	2	N/A	Alpha	O	185 KIAS	N	0
8-9	2	N/A	Alpha	O	185 KIAS	N	0
9-1	3	N/A	Alpha	O	185 KIAS	N	0
9-2	3	N/A	Alpha	O	185 KIAS	N	0
9-3	3	N/A	Alpha	B	185 KIAS	N	0
9-4	3	N/A	Alpha	B	185 KIAS	N	0
9-5	3	N/A	Alpha	O	185 KIAS	N	0
9-6	3	N/A	Alpha	O	185 KIAS	N	0
9-7	3	N/A	Alpha	O	185 KIAS	N	0
9-8	3	N/A	Alpha	B	185 KIAS	N	0
9-9	3	N/A	Alpha	O	185 KIAS	N	0
10-1	1	N/A	Alpha	B	185 KIAS	N	0
10-2	1	N/A	Alpha	B	185 KIAS	N	0
10-3	1	N/A	Alpha	O	185 KIAS	N	0

APPENDIX E. DATA ANALYSIS PLAN

The data analysis plan used in reducing and analyzing the flight test data followed the same process used for the Large Amplitude Multimode Aerospace Simulator (LAMARS) data. While at the off-station facility, copies were made of both the parametric data for each run as well as any audio or video recordings. Each data run was given a number, so that it could be more easily organized after testing was complete. On each data run, a hard copy of a test card was used by the test conductor to record both pilot comments and initial performance parameters. During testing, test team members created excel spreadsheets to input Cooper-Harper ratings and performance data in order to get a real time quick-look of trend data on how the testing was proceeding. When the test team returned to Test Pilot School (TPS), the data were analyzed in order to determine whether each objective was met. After LAMARS, the goal of the data reduction was to set a baseline to compare to Total In-Flight Simulator (TIFS) testing and to prepare Matlab, Excel, and other data reduction techniques to streamline the effort when reducing TIFS data.

At Calspan, a DVD of all the recorded in-flight parameters for each flight was made. TIFS also had a video camera in the evaluation cockpit to record an over the pilot's shoulder view of the testing. DVDs from each flight were gathered by the test team. During each flight, the test conductor again recorded pilot comments and initial parameters on a hard copy of each test card, which were marked with a run number. A run number for all the programmed test inputs and semi-closed loop maneuvers was also recorded. After each flight, the pilot summarized their comments on the flight and wrote them in a daily flight test report. This daily flight test report included lessons learned in testing that would aid the subsequent pilots and test conductors in their data flights. Cooper-Harper ratings and performance information were again inputted into an Excel spreadsheet, to provide a quick-look on trend data. This process continued between each flight. After flight testing was completed, a brief with Calspan was conducted to summarize the quick-look results and gather any preliminary lessons learned.

After returning to TPS, the flight test engineers took the data a reduced it according to each test team objective. For the first objective, Cooper-Harper ratings of the baseline system were summarized on a histogram according to both task and individual pilot. For the second objective, Cooper-Harper ratings for both the baseline and optimized system were compared according to both task and pilot. Pilot performance using both of the systems was also compared. Another comparison between the baseline and optimized system was made by plotting pilot aggressiveness and duty factor. Finally, for the third objective, the model following capability of the TIFS was displayed. This included flight conditions with both calm conditions and with turbulence.

The LAMARS data was then looked at again from the perspective of pilot aggressiveness and duty factor, so that a comparison could be made between LAMARS and TIFS. The data were then divided and presented in the technical report.

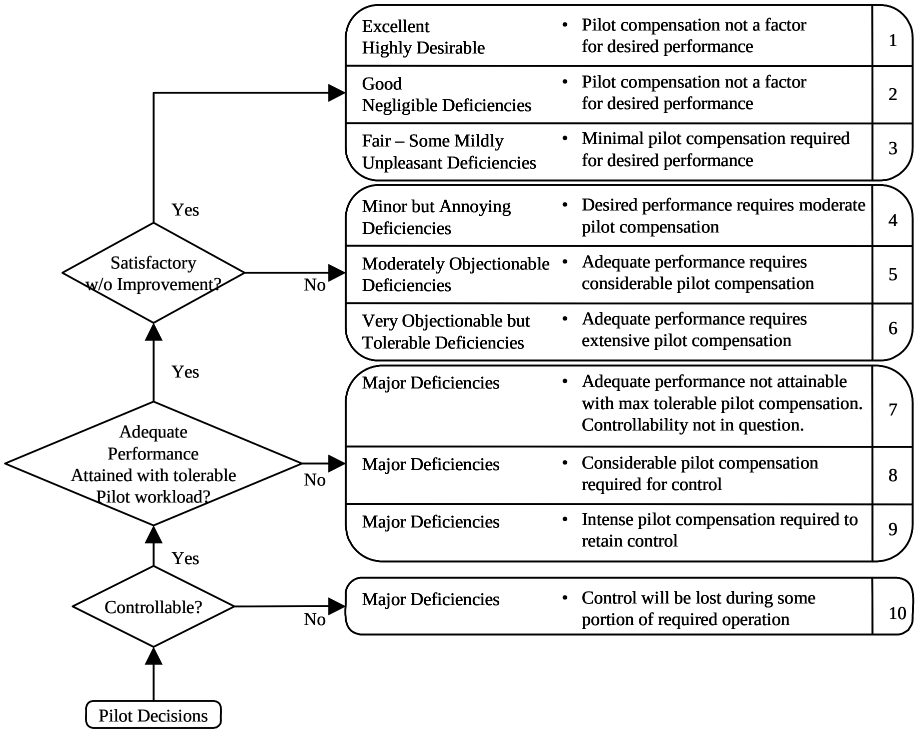

Figure E-1. Cooper-Harper Rating Scale

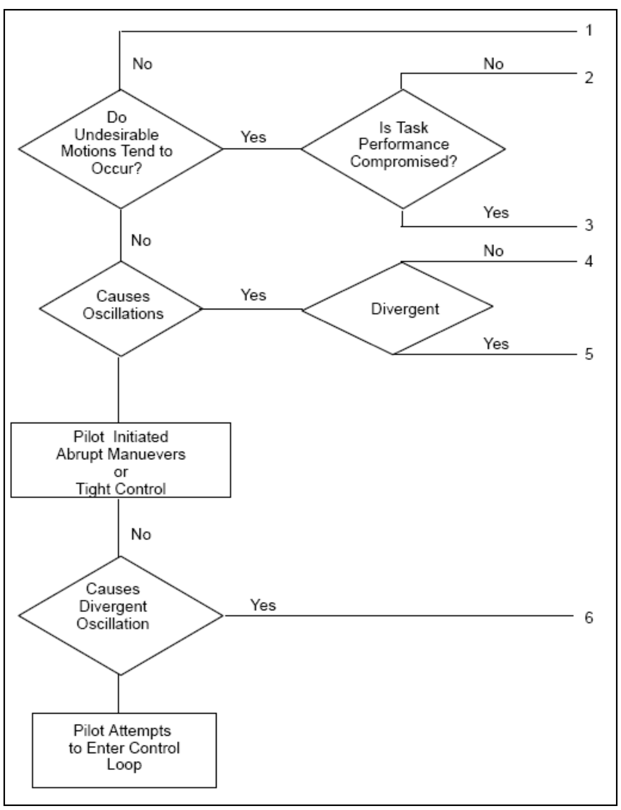

Figure E-2. PIO Rating Scale

APPENDIX F. PLOTS OF RESULTS

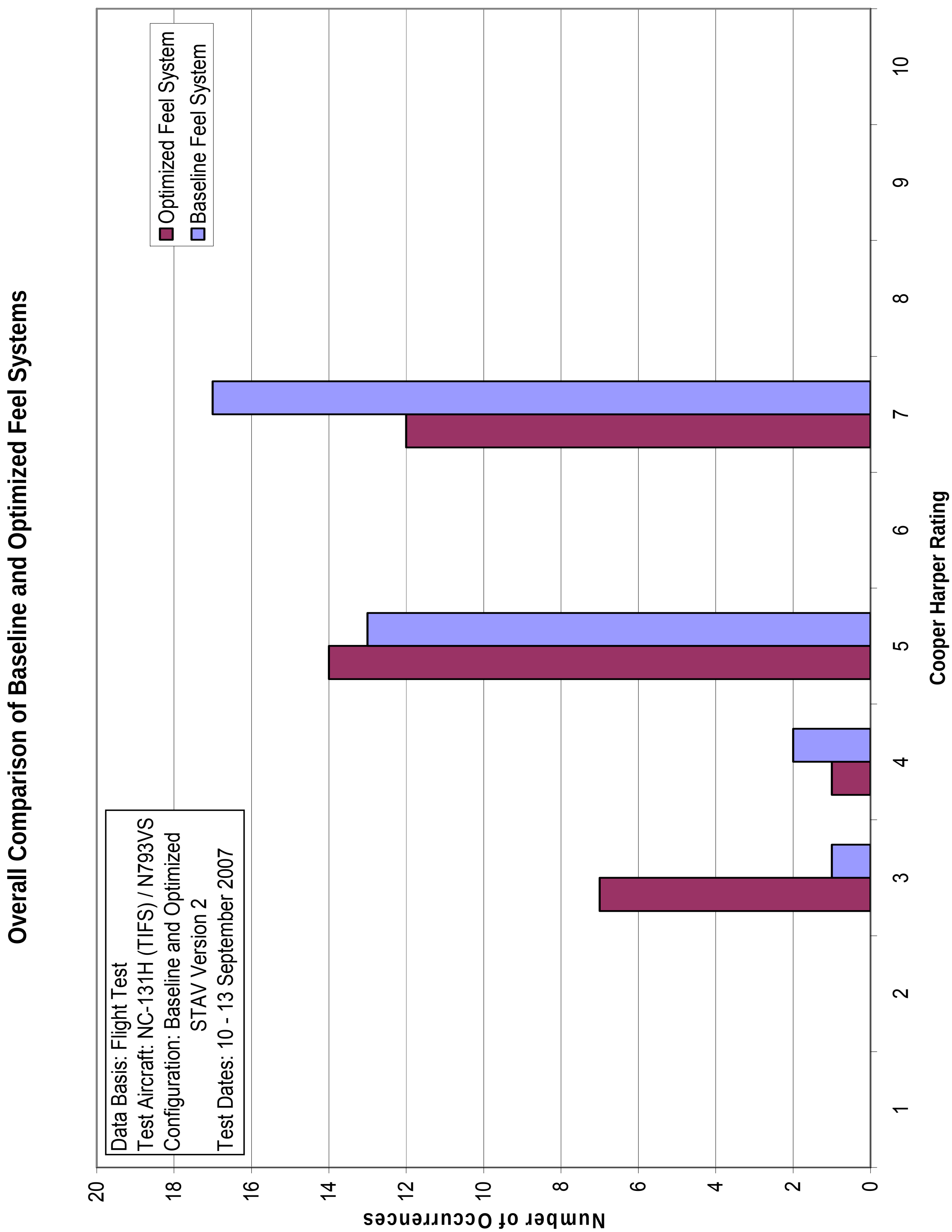

Figure F-1. Overall Comparison of Baseline and Optimized Systems

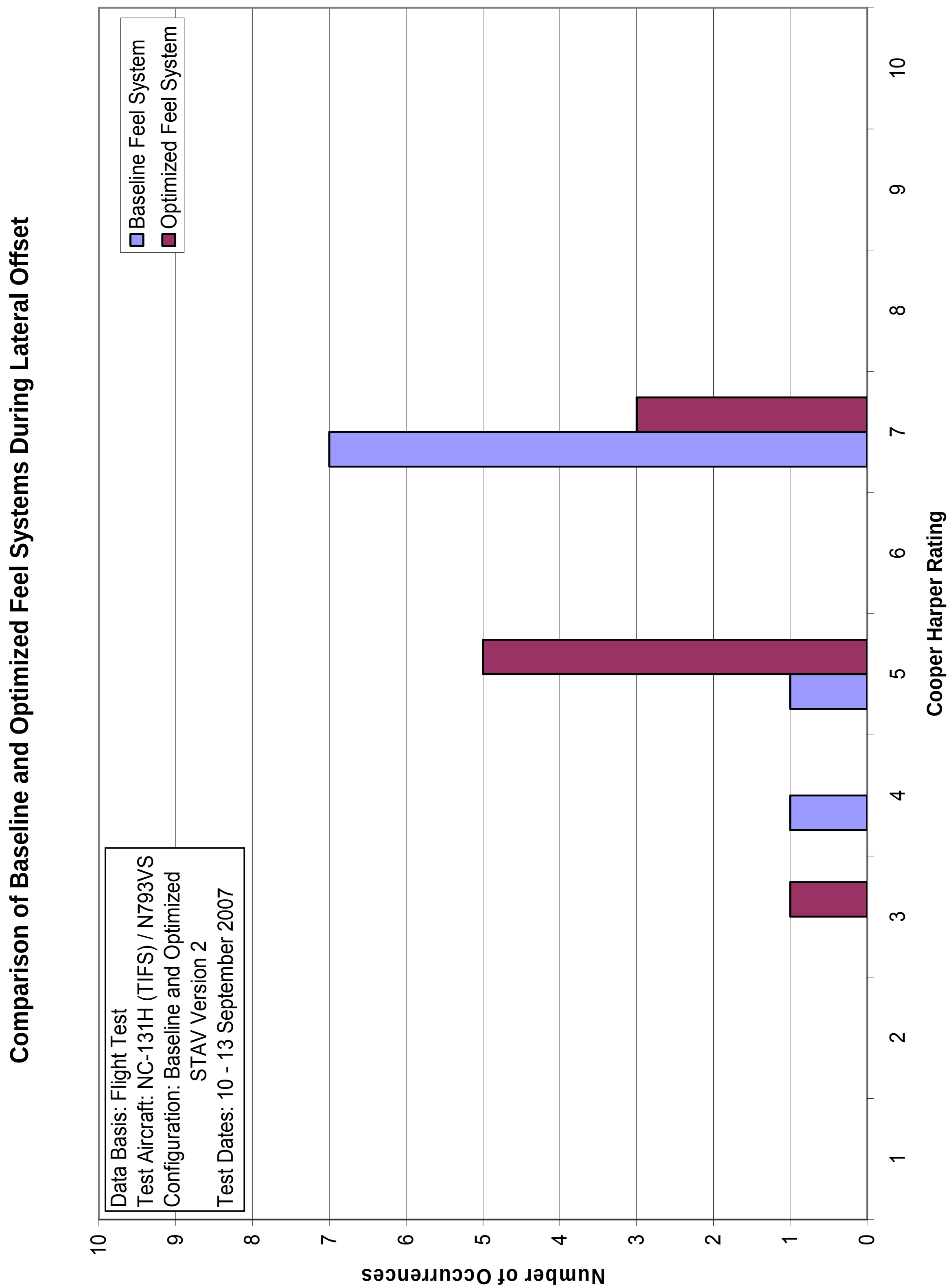

Figure F-2. Comparison of Baseline and Optimized Systems During Lateral Offset

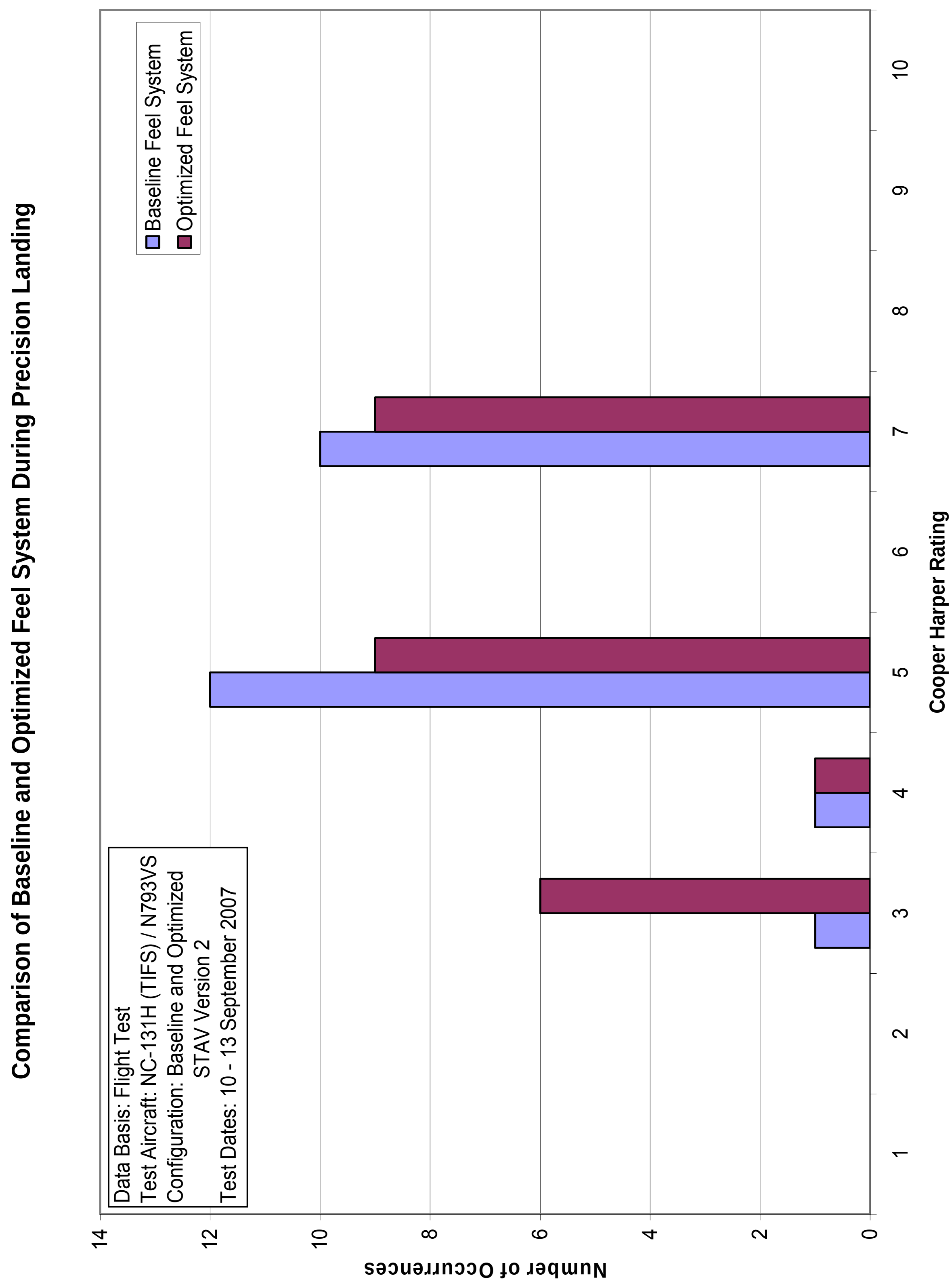

Figure F-3. Comparison of Baseline and Optimized Systems During Precision Landing

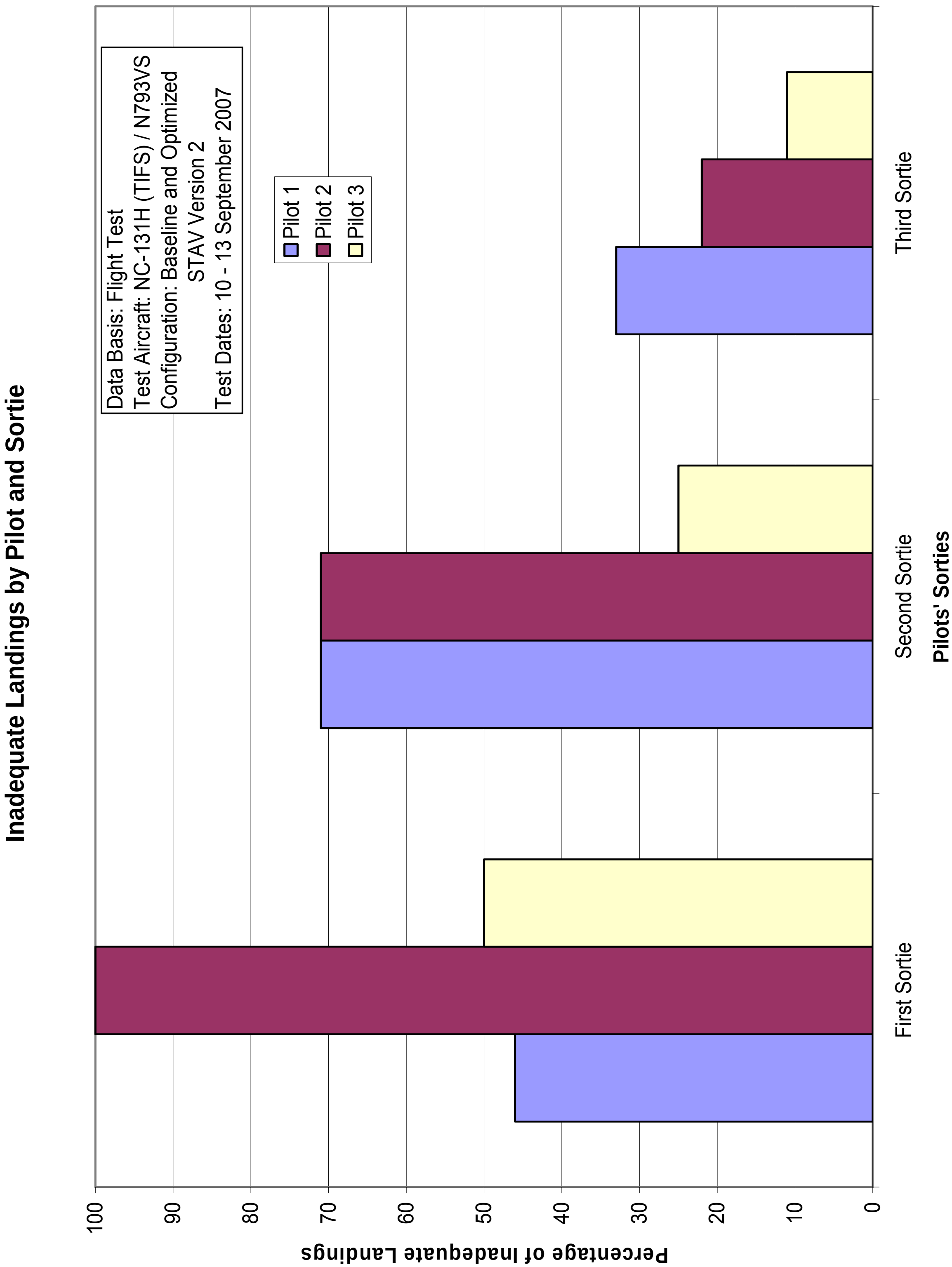

Figure F-4. Inadequate Landings by Pilot and Sortie

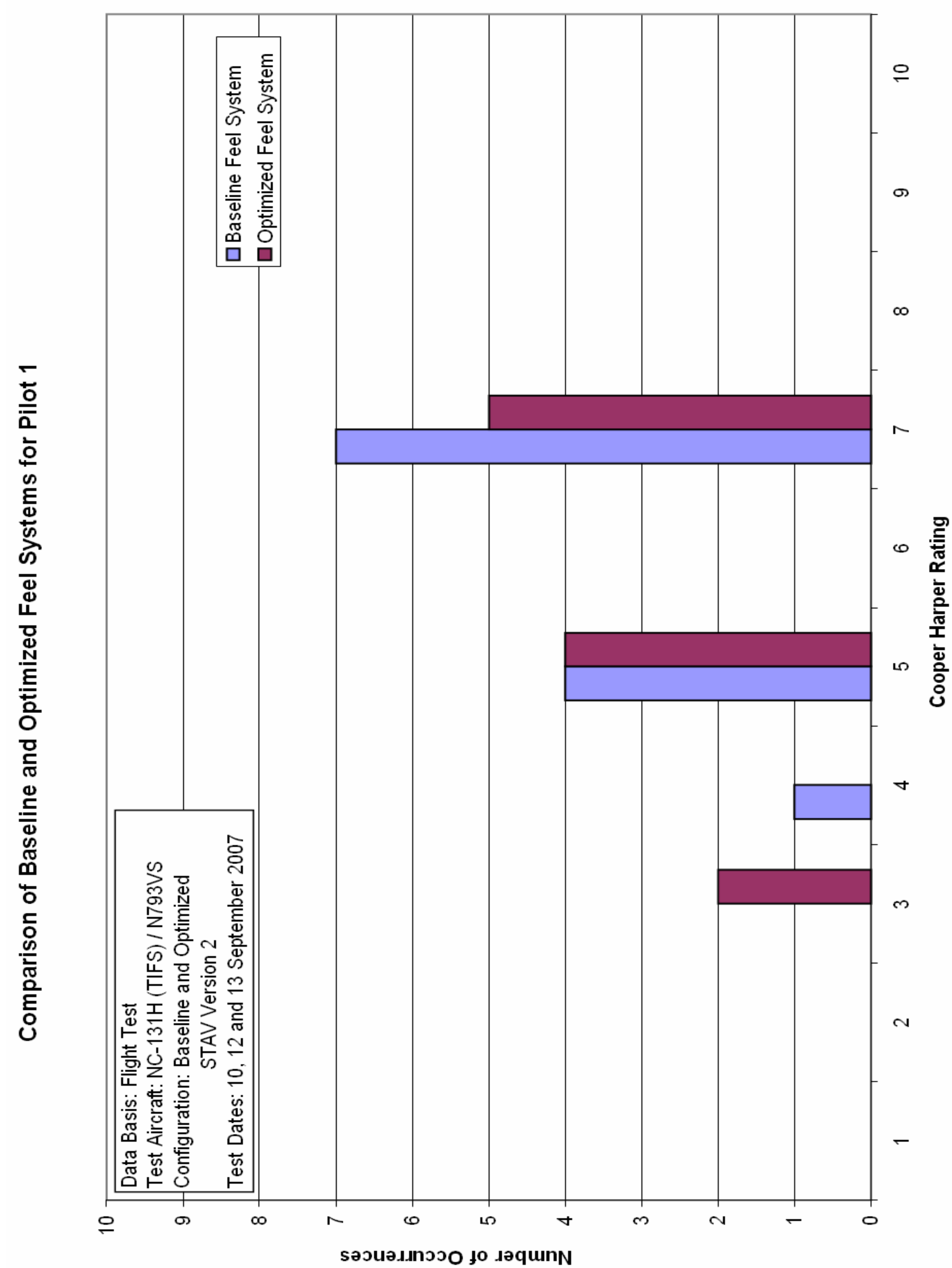

Figure F-5. Comparison of Baseline and Optimized Systems for Pilot 1

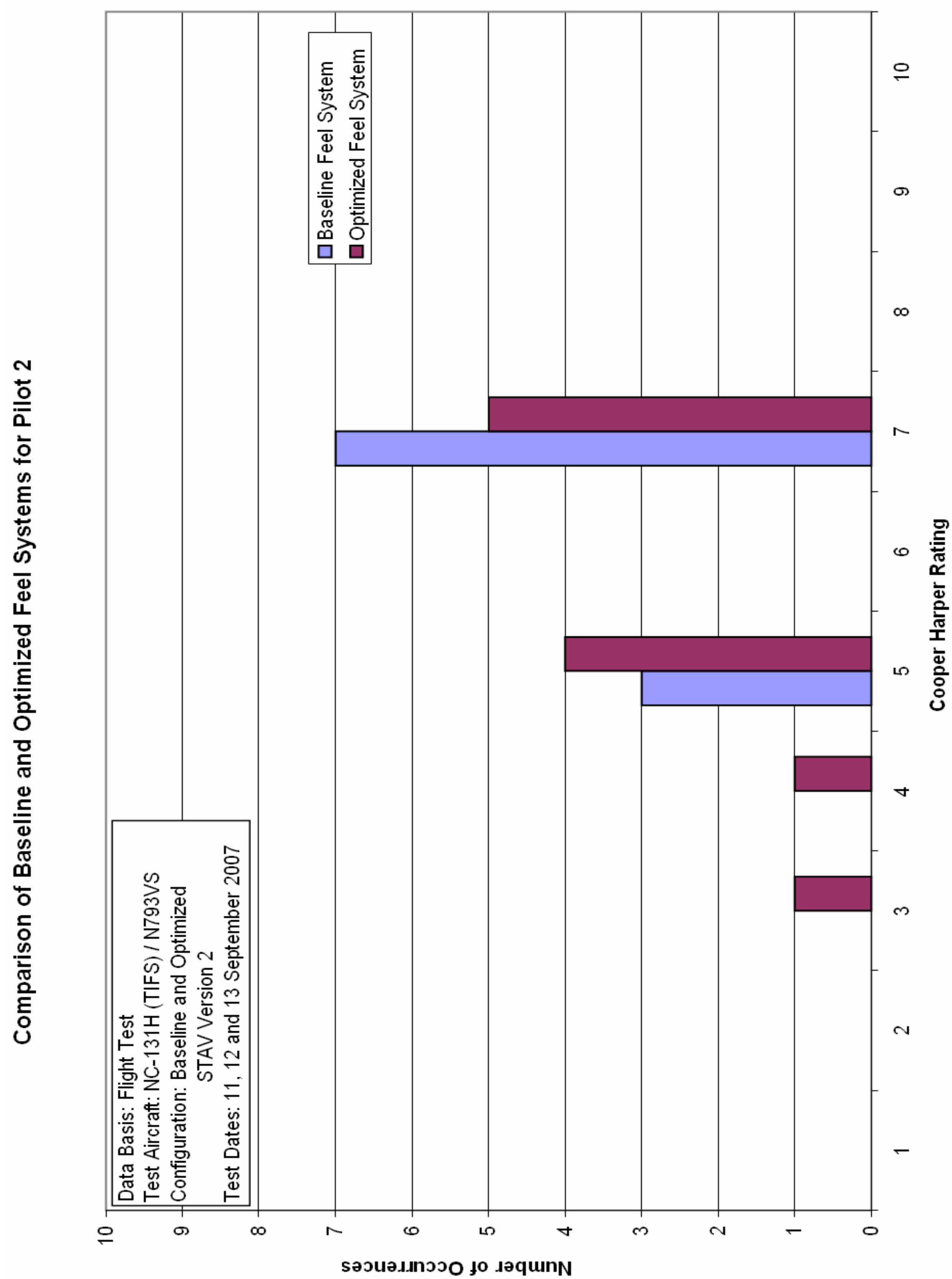

Figure F-6. Comparison of Baseline and Optimized Systems for Pilot 2

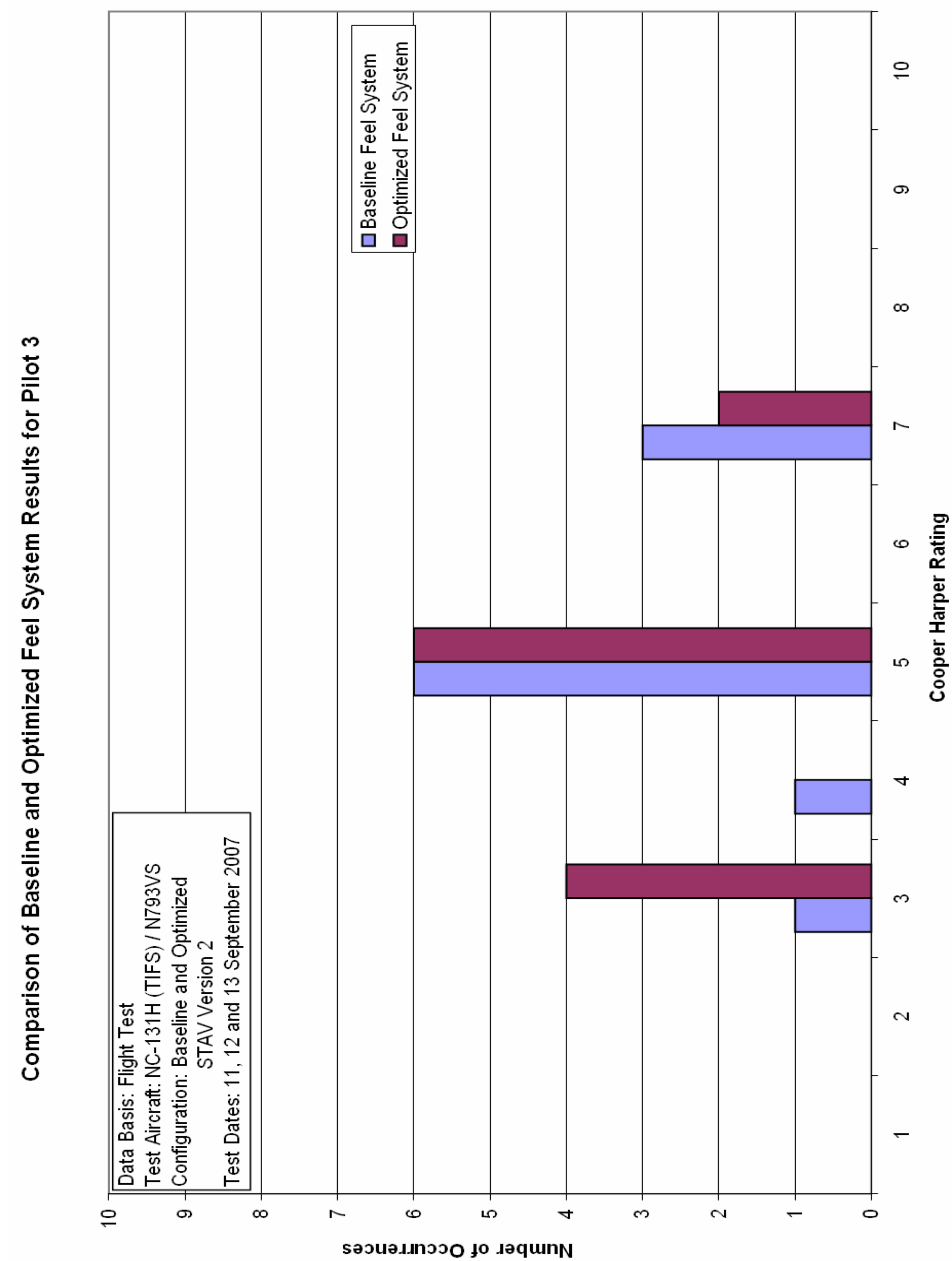

Figure F-7. Comparison of Baseline and Optimized Systems for Pilot 3

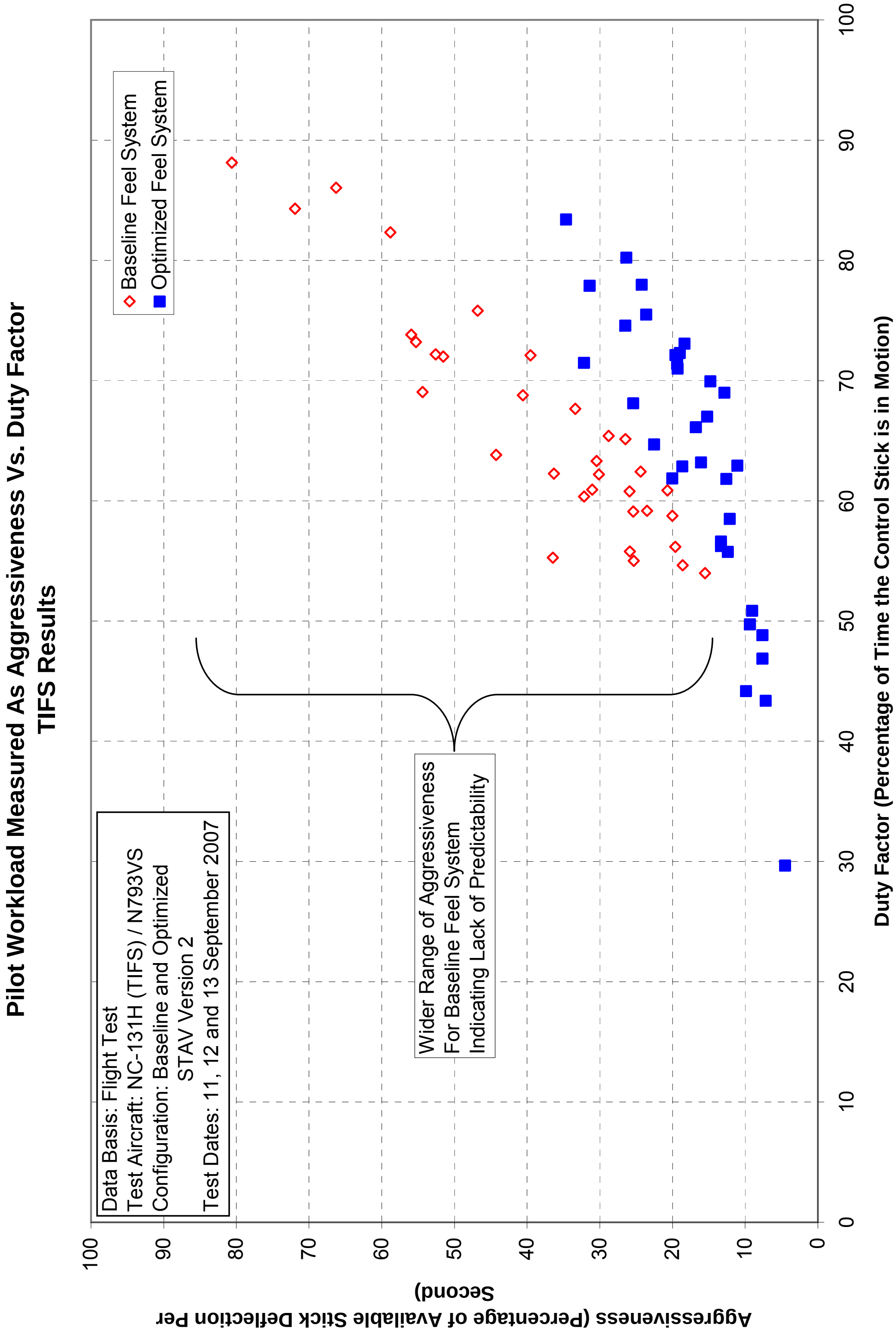

Figure F-8. Pilot Workload Measured as Aggressiveness vs. Duty Factor

Table F-1. Landing Details for Baseline and Optimized Systems with Inadequate Results

Table F-1. Landing Details for Baseline and Optimized Systems with Inadequate Results

Number of Baseline Landings with Inadequate Results	17

Mission #	Record #	Reasons for Baseline System Inadequate Results	Length	ROD	Pitch	A/S
2498	6	Rate of Descent: 8.1; Touchdown A/S: 158		X		X
2498	16	Rate of Descent: 6.2		X		
2498	19	Landing Length: 1636	X			
2499	5	Touchdown A/S: 162				X
2499	8	Touchdown A/S: 147; Pitch: 15.7			X	X
2499	11	Touchdown A/S: 138; Pitch: 15.8			X	X
2499	14	Rate of Descent: 9.8; Touchdown A/S: 134; Pitch: 15.2		X	X	X
2499	20	Landing Length: 1599; Rate of Descent: 8.4; Touchdown A/S: 137	X	X	X	
2500	22	Landing Length: 1728	X			
2500	23	Rate of Descent: 8.6; Touchdown A/S: 160; Pitch: 15.4		X	X	X
2500	26	Touchdown A/S: 162; Pitch: 15.0			X	X
2500	27	Pitch: 18.1			X	
2501	21	Rate of Descent: 7.7		X		
2501	39	Rate of Descent: 9.5		X		
2501	42	Rate of Descent: 9.0		X		
2501	43	Rate of Descent: 6.4		X		
2502	5	Rate of Descent: 6.3		X		
2503	5	Landing Length: 2529	X			
			4	10	7	8

Number of Optimized Landings with Inadequate Results	12

Mission #	Record #	Reasons for Optimized System Inadequate Results	Length	ROD	Pitch	A/S
2498	26	Landing Length: 2101	X			
2498	28	Rate of Descent: 8.9		X		
2498	31	Rate of Descent: 6.5		X		
2500	5	Landing Length: 2197 and touchdown A/S: 163	X			X
2500	8	Landing Length: 2343	X			
2500	11	Rate of Descent: 10.9		X		
2500	20	Landing Length: 1622	X			
2501	21	Rate of Descent: 7.7		X		
2501	40	Landing Length: 2104	X			
2501	44	Rate of Descent: 6.8		X		
2502	17	Landing Length: 2079	X			
2502	25	Rate of Descent: 7.1		X		
			6	6	0	1

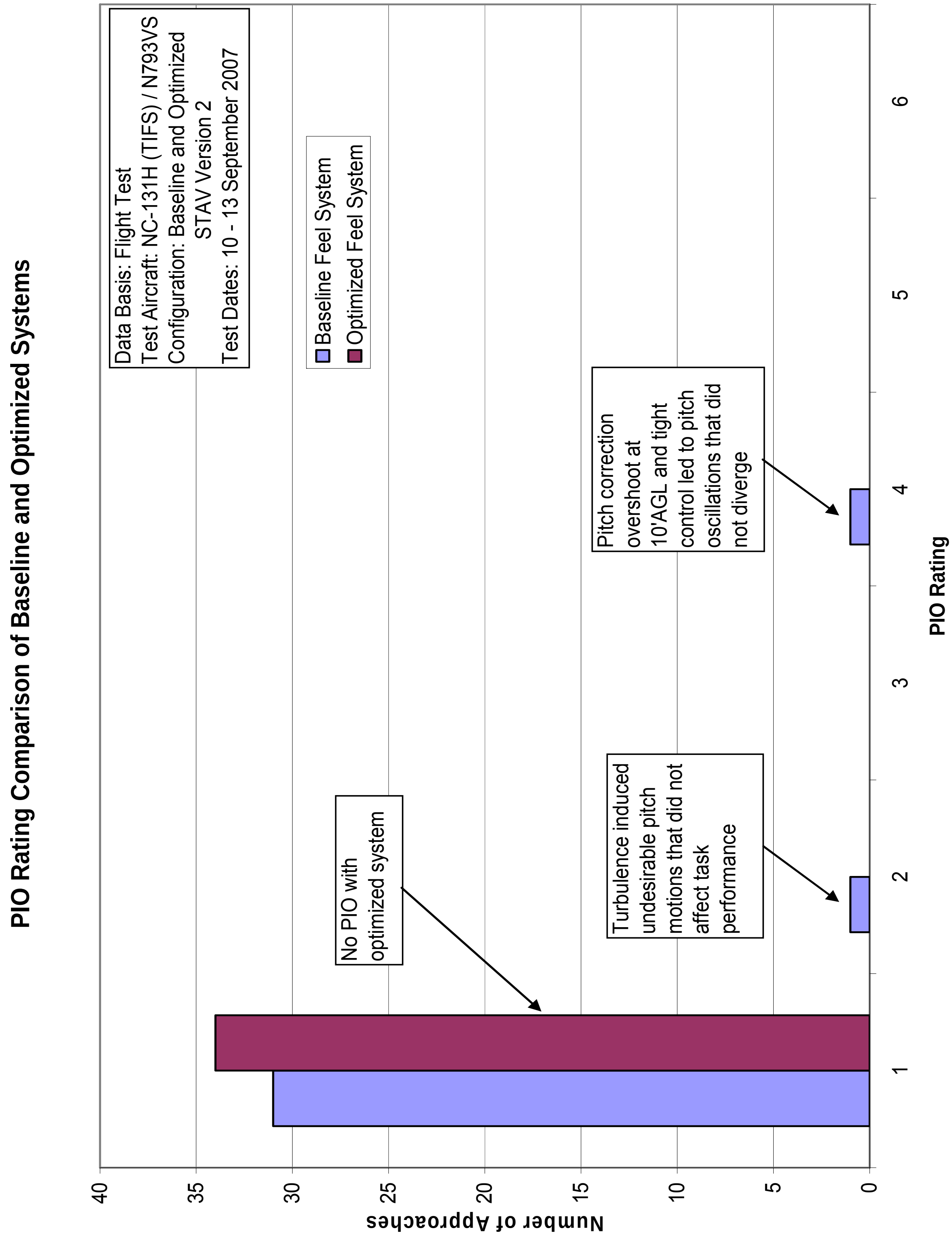

Figure F-9. PIO Rating Comparison of Baseline and Optimized Systems

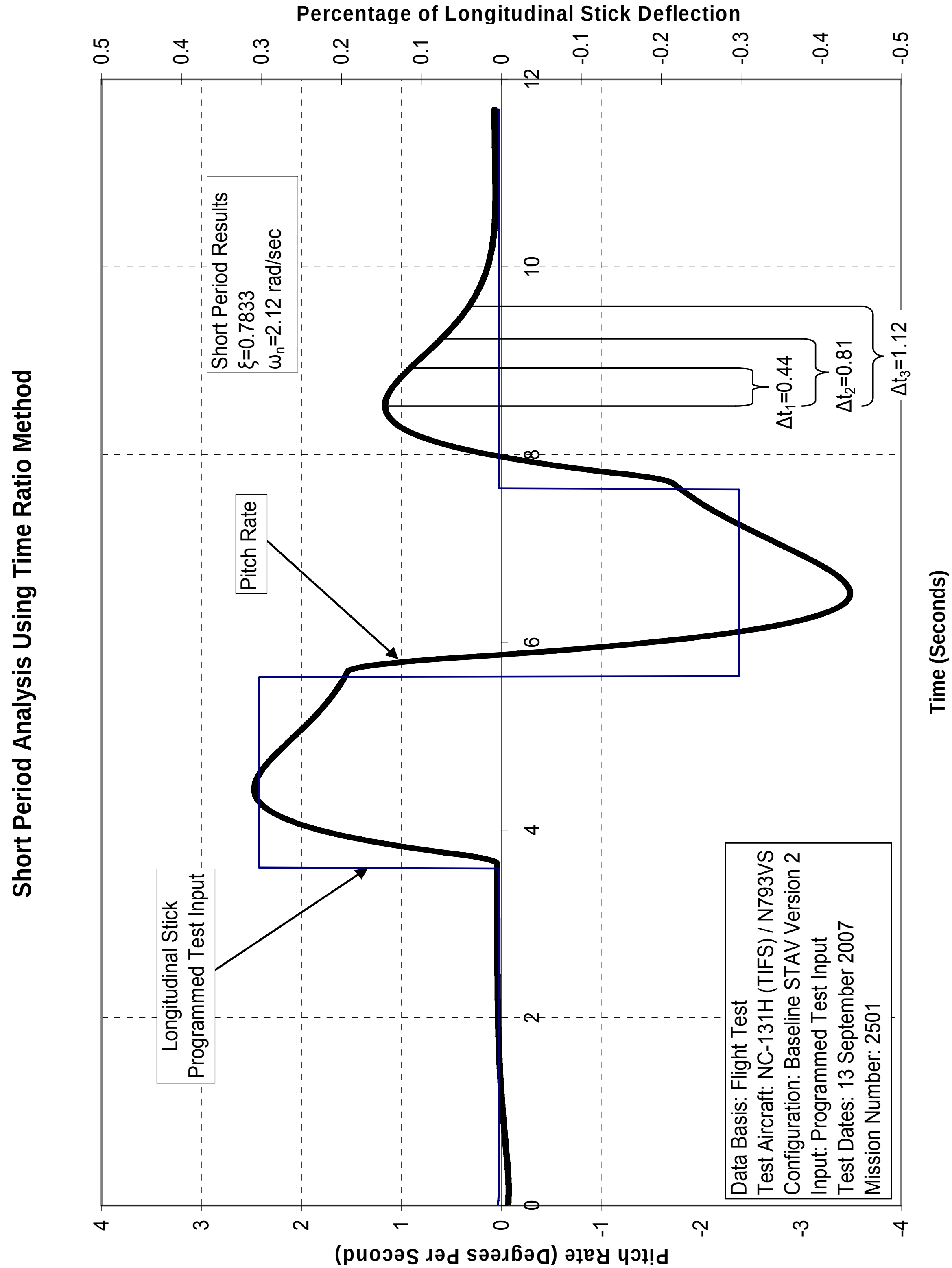

Figure F-10. Short Period Analysis using Time Ratio Method

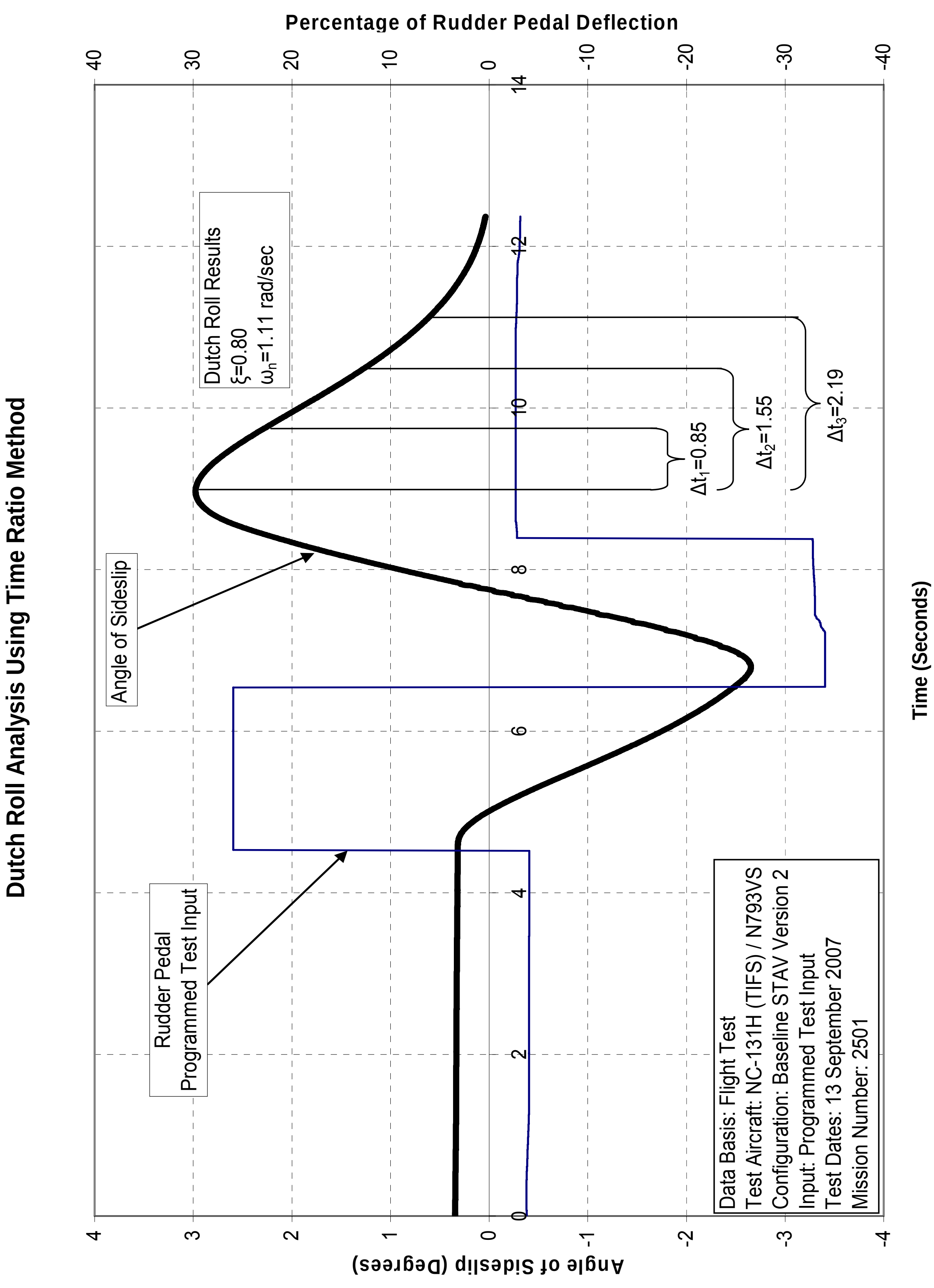

Figure F-11. Dutch Roll Analysis Using Time Ratio Method

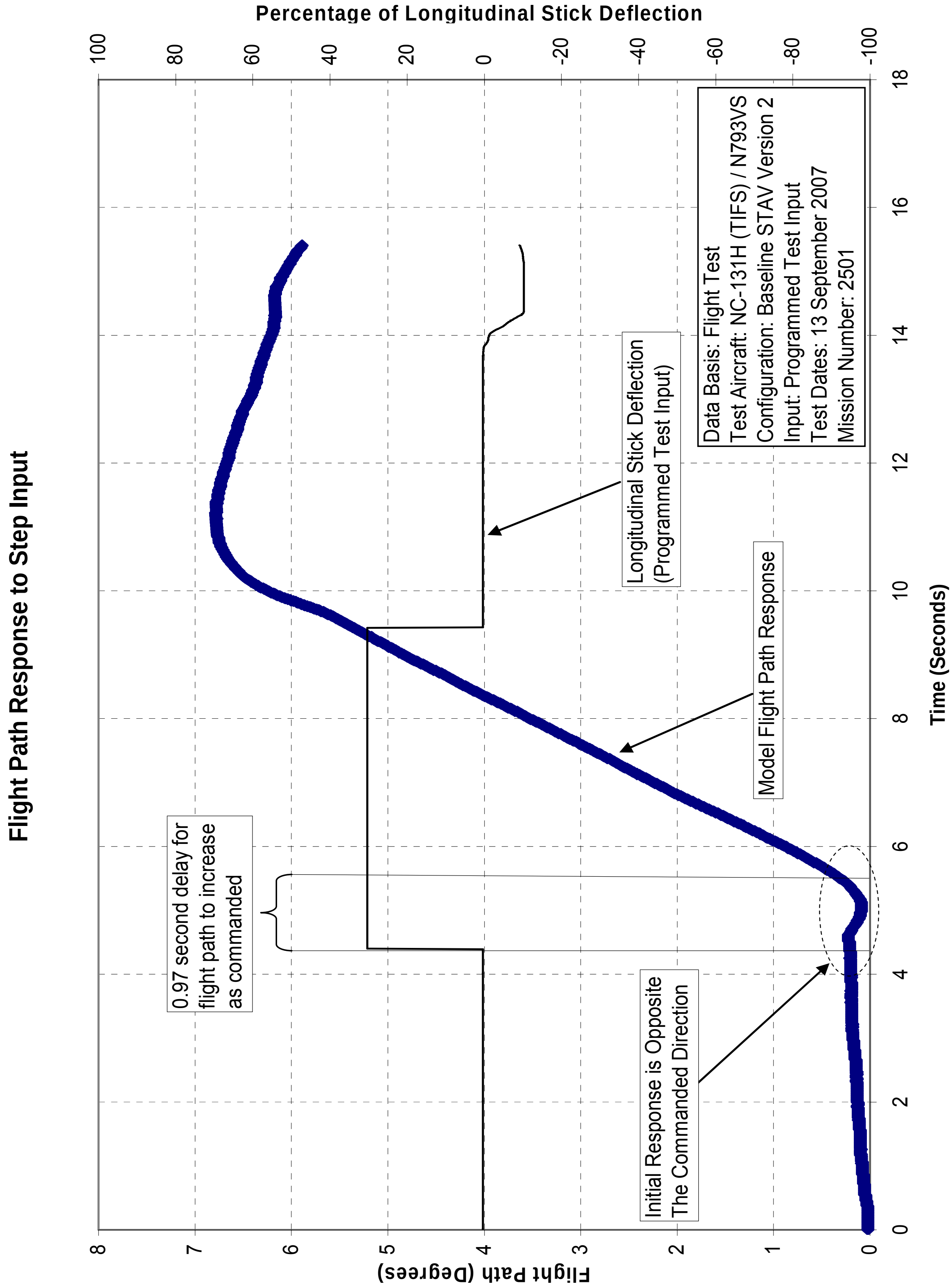

Figure F-12. Flight Path Response to Step Input

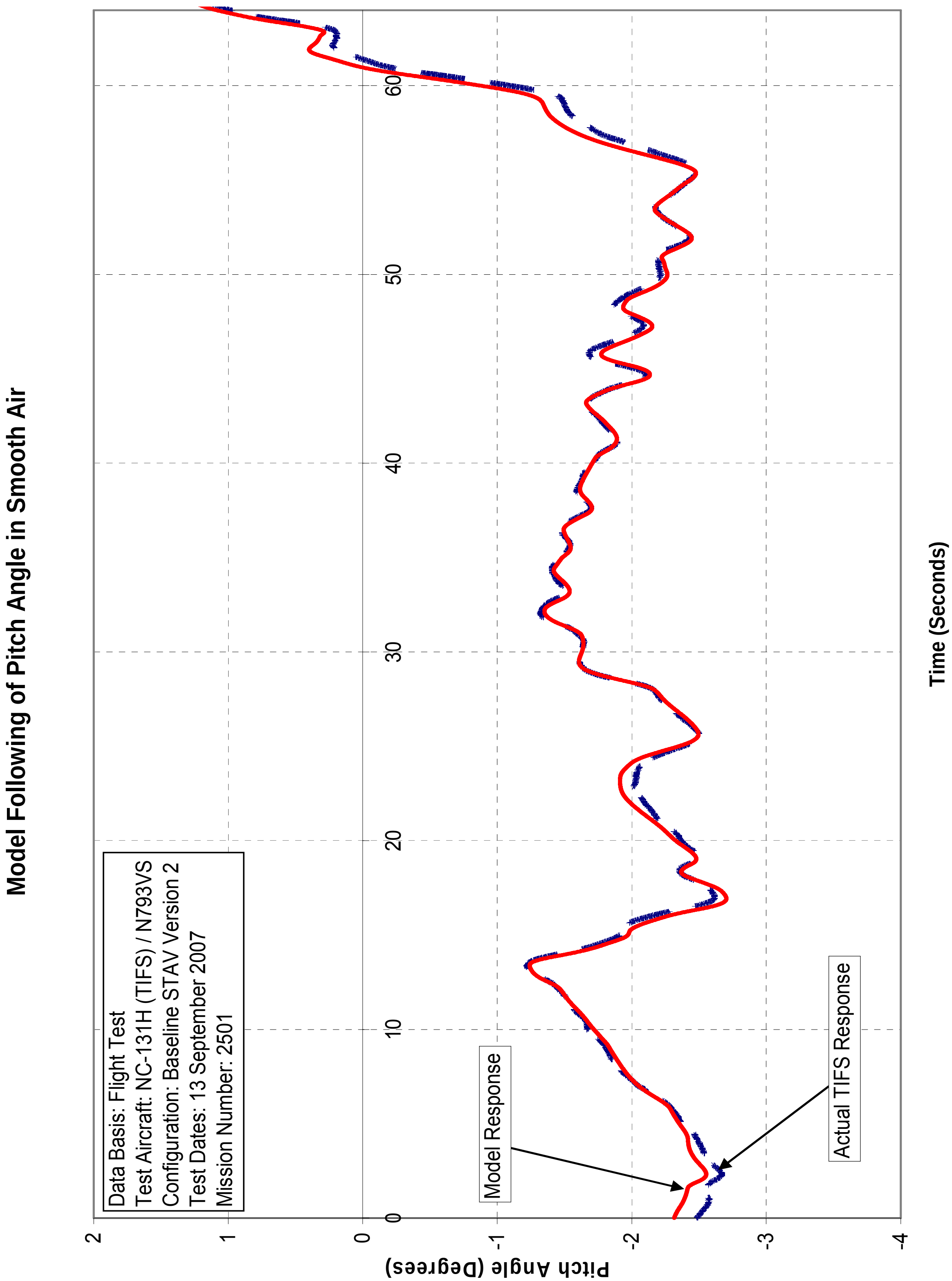

Figure F-13. Model Following of Pitch Angle in Smooth Air

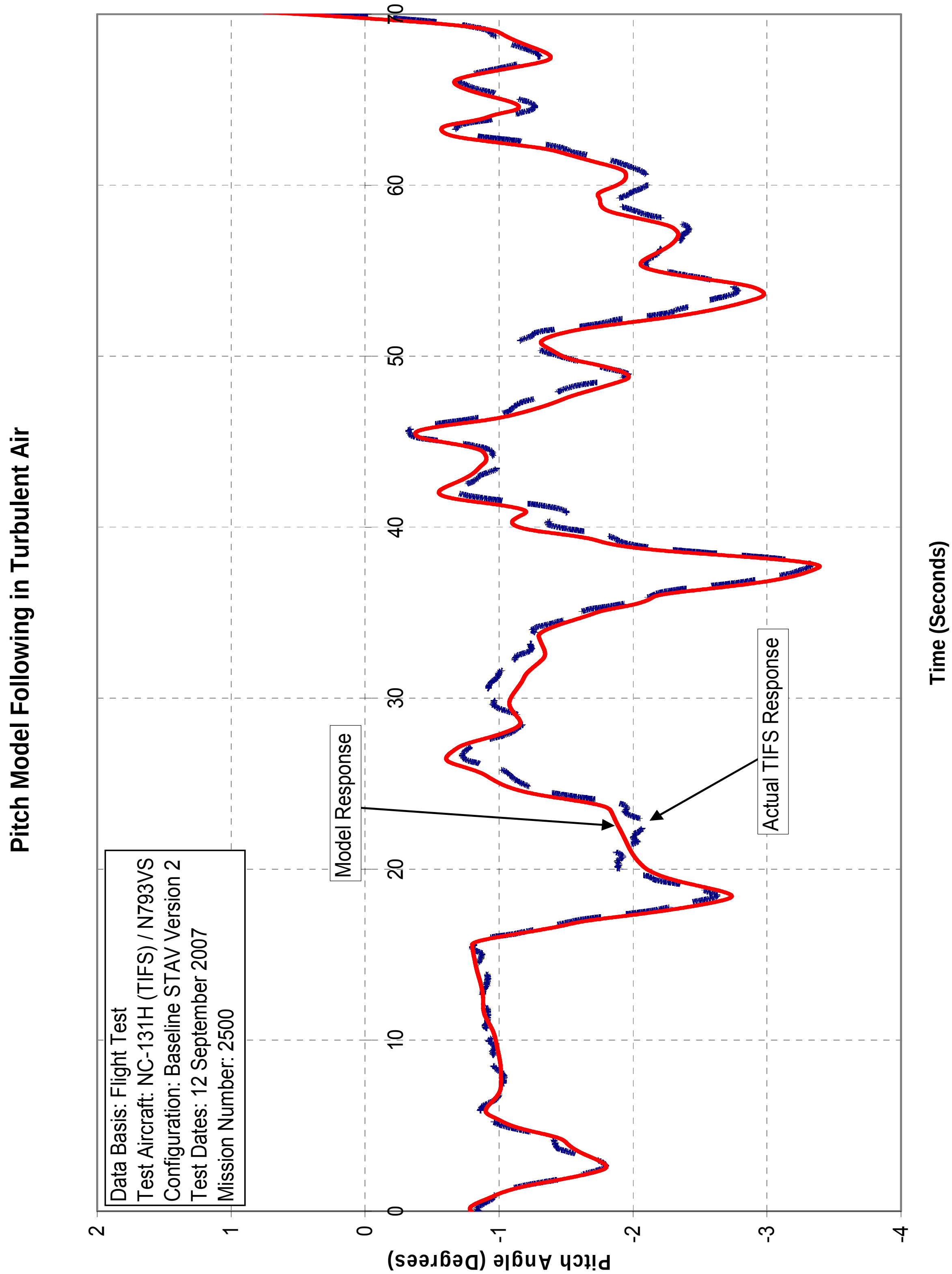

Figure F-14. Model Following of Pitch Angle in Turbulent Air

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APPENDIX G. LESSONS LEARNED

- Test management projects that can potentially be accomplished off-station should be run through a costs and benefits analysis to determine if the decision to conduct the Test Management Project (TMP) while at an off-base facility makes sense, from both a technical and risk standpoint. Conducting the TMP flight testing away from Edwards carries significant risk, in the fact that the schedule is constrained by Test Pilot School (TPS) scheduling requirements. The maximum realistic time away is one five-day work week. When possible, the weekends should be used to travel to minimize the impact on the TPS schedule and to acclimatize the test team to the new conditions, especially if there is a significant time change involved. The flight test schedule is put at risk by both weather and maintenance factors, which could effectively prevent or at best severely limit the number of flight test sorties accomplished. However, the benefits of having contractor facilities, personnel, and equipment on site minimizes some of the maintenance risk, while scheduling the testing according to predicted weather patterns can reduce the weather risk. Try to front-load the schedule as much as possible to allow for any potential flight test delays. This may entail early morning take-offs and triple turns, but the test team must be flexible. If the testing is going to involve traffic pattern work, then testing at an offsite location with minimal traffic can increase the amount of data collected and minimize the impact of air traffic control. The test team can also focus all of their efforts on the project, and not worry about other TPS syllabus events.

- When possible, simulations of the flight testing should be accomplished prior to the flight testing. This forces the test team to create test cards and run them, so that any mistakes can be worked out prior to wasting flight test time. It also allows the test team to practice the cadence of the testing itself, so that all evaluator pilot and test conductor duties are clearly understood before testing begins. Testing in a simulator allows the test team to create data analysis and reduction tools, something that can streamline the actual flight data reduction. This is particularly valuable when testing on a tight schedule, because a quick-look at the data can allow small modifications to be made to the testing, something that could not be accomplished if all data reduction was saved until after flight test. Finally, it is imperative that the test team integrate with the simulator technicians early in the test process. A team of technicians that is intimately familiar with the test program provides better adaptability when test procedures must be altered or simulator problems arise. The Air Force Research Laboratory Large Amplitude Multimode Aerospace Simulator (LAMARS) technicians provided exemplary support throughout the project, and provide a fantastic example of properly conducted simulator testing.

- When conducting tests, the test team must always remember who retains test control. The test team must reference the test plan, especially when testing is not proceeding as planned or when actual results do not match predictions. This will help to prevent the test objectives from changing during testing.

- Contracting issues should be accomplished as early in the TMP process as possible. When dealing with multiple contractors, it can be very easy to lose the scope of the testing and become bogged down in the paperwork. Contracts should be provided to and reviewed by the test team, to ensure that no important factors are omitted (i.e. who pays for the fuel).

- Whenever possible, try to have the contractors attend the test plan working group and technical review board in person. It is much easier to discuss technical procedures face to face than it is via a teleconference. The risk of a miscommunication in testing procedure or capability is much higher when conducting all meetings remotely.

- The test team must take model limitations into account during testing, and must be flexible in their test design to account for unforeseen changes in the model. Current model predictions were based on a constant center of gravity location and aircraft configuration, and testing was designed to take this into account. The instantaneous center of rotation was initially thought to be in front of the actual aircraft, and the test team expected the pilots to feel a motion that was opposite the initial inceptor input. However, the pilots did not perceive this motion during simulator testing. After this simulator testing was conducted, it was discovered that the previous location for instantaneous center of rotation was incorrect. The correct instantaneous center of rotation was nearly collocated with the cockpit, and explained the motions perceived by the pilots. The design of the test plan and objectives minimized the impact of this change, and allowed the team to proceed with flight testing without altering the test plan.

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